ECONOMETRIC AND DECISION ANALYSIS STUDIES IN
RESEARCH AND DEVELOPMENT
IN THE
ELECTRONICS INDUSTRY

by

HOWARD THOMAS, B.Sc.,M.Sc.,M.B.A.

Ph.D, University of Edinburgh, 1970

ACKNOWLEDGEMENTS

In writing a thesis of this length and breadth there are inevitably a large number of people to whom I would like to express my thanks. None of them are in any way responsible for the material in the thesis but they have each given something of their time and encouragement to further the development of this work on research and development.

Perhaps the best way to acknowledge their help is to list them in random order. First, thanks to the managing directors and research personnel in firms A and B for their cooperation in the research. Without them this thesis would have been an empty skeleton. Second, thanks to the members of my thesis committee Professor J. N. Wolfe, Professor P. Vandome, Dr. F. R. Himsworth and Mr. P. R. Fish (coopted) for their discussions in which several difficult points were clarified. Third, thanks to Dr. David Edge of the Science Studies Unit, University of Edinburgh for his encouragement and liberal attitude towards the removal of half of the books from his library. Fourth, thanks to David Muxworthy and, in particular, John Murison of the Edinburgh Regional Computing Centre for their help with the programming and execution of many of the simulation runs in Chapter 4. Fifth, to my two departmental heads Professor N. C. Hunt of Edinburgh University, Department of Business Studies (under whose encouragement and guidance this research was first developed) and Professor P. G. Moore, London Business School. I wish to express my thanks for their encouragement and kindness in allowing me a number of short periods in which I could concentrate solely on the thesis. Sixth, thanks to the two secretaries at the London Business School, Miss Lynn-Carole Jonas and Miss Geraldine Madden, who have cheerfully produced an ordered typescript from my slightly unreadable writing. Finally, and most important, I would like to thank my wife and son for cheerfully putting up with the idiosyncracies of a husband doing research part time and lecturing full time.

Econometric and Decision Analysis Studies in R and D in the Electronics Industry

Abstract of Thesis

This thesis is an attempt to contribute to the understanding of the research and development process at the level of the firm. The existing economic evidence on research and development lacks thorough understanding of the nature of the inventive process, even though the volume sponsored by the National Bureau of Economic Research, "The Rate and Direction of Inventive Activity", points to the strikingly micro-character of R and D activity.

The thesis has several major objectives:- First, to review the existing economic evidence on research and development and to point to any firm conclusions from the evidence. Second, to describe the nature of research and development in the firm, the characteristics of the inventive process and the decision process in R and D and the nature of uncertainty inherent in R and D activity. Third, to accumulate retrospective evidence on the efficiency of research and development in the firm. Fourth, to try and build operationally useful models to help R and D management cope with the sequential, groping and uncertain nature of R and D activity. These models stress the use of concepts from statistical decision theory and capital budgeting and are based on the decision process analysis work carried out in the firms. Fifth, to evaluate the usefulness and relevance of the rational theories of statistical decision theory in aiding the solution of the R and D decision under uncertainty.

The thesis is divided into five parts which present results under each of the five above headings. Throughout the emphasis is on econometric and decision analysis work and parts (ii) to (v) are based on empirical evidence obtained from a case study sample of firms in the electronics industry in Scoreland.

The final section discusses the usefulness of the research work and suggests further model-building approaches. Decision theory is found to be more useful on a conceptual rather than on a practical level because of the uncertain character of R and D activity.

CONTENTS

ECONOMETRIC AND DECISION ANALYSIS STUDIES IN RESEARCH AND DEVELOPMENT IN THE ELECTRONICS INDUSTRY.

INTRODUCTION

The economics of research and development is an area which is attracting increasing interest from economists and operational research workers. One of the main reasons for this interest is the extent of government sponsorship of research in both Britain and the United States. The reasons for this sponsorship derive from such policy needs as the drive for technological change in British industry and the huge efforts expended through NASA space programs and the Vietnam war effort in the United States.

A large number of articles has appeared in the management journals explaining to businessmen how they should manage and plan their research activities. Almost without exception these articles show scant awareness of the structure and economic characteristics of the research and development process at the firm level. Mansfield (1) goes further and states that the scientific content of such articles tends to be very low. He makes out

---

(1) E. Mansfield, "Economics of R and D:- A Survey of Issues, Findings and Needed Future Research", In V. Terpstra ed. Patents and Progress; New York: J. Wiley, 1965.

a case for the study of research and development at the firm level pointing out the paucity of knowledge with regard to such things as the nature of research and development, the composition of a firm's R and D portfolio and the determinants of the size of the R and D budget.

This thesis is concerned with the decision processes in research and development and builds very much upon the work of Mansfield(2) and the RAND Corporation economists,(3) who pioneered the detailed study of R and D at the firm level. It tries to outline and make clear the nature of the research and development decision under uncertainty. As such it draws heavily upon both the decision theory (where we define decision theory in the narrow statistical and the broader normative economic context) and the capital budgeting literature. Some of the problems considered are the resource allocation decisions of what projects to support and how much to spend on them given an objective of maximising the return from a given budget.

However, in order to suggest "normative" models to aid R and D decision-makers in making decisions under uncertainty our first aim must be to describe the decision process and spell out the nature of the uncertainties and how they vary through time.

---

(2) E. Mansfield, Econometric Studies of Industrial Research and Technological Innovation, New York: W. W. Norton, 1968.

(3) Some of this work is summarised in Rate and Direction of Inventive Activity - R. R. Nelson (ed.), Princeton: 1962.

A major objective in this study is thus to describe in great detail how firms actually make decisions in R and D. For example, we consider what information decision-makers draw upon and how far they are constrained by the structure of the organisation within which they operate. It is considered vital that the processes are sufficiently well documented and understood before any attempt is made to construct operationally realistic models of the R and D process. The second aim of the study is then to suggest model-building approaches in R and D and, particularly, to discuss the usefulness and relevance of the rational theories of statistical decision put forward by the Harvard decision School.[4]

The reasons for studying the research and development decision rather than other decision problems at the firm level are an amalgam of several different motives. First, a study of the economics of science in general was commissioned under Professor J. N. Wolfe of Edinburgh University and fortunately the author was asked to contribute to the work because of his interest in decision theory. This interest had previously led him to do some pilot work on the marketing decision problems of a firm in the Edinburgh area which he had decided to abandon because of the lack of data and implementation of marketing concepts in the firm concerned. As this firm was suggested by many colleagues to be typical of most of those in South East Scotland

(4) See, for example, R. Schlaifer, Probability and Statistics for Business Decisions, New York: McGraw-Hill, 1959.

with marketing interests a decision to abandon the marketing area was thus taken. Second, the research and development decision, like the new product decision problem in marketing, is a good example of a decision problem under uncertainty. Third, the expansion of the electronics industry in Scotland has been a rapid post-war phenomenon and the captive audience and co-operation of some of these firms was essential to the conduct of the study. Fourth, to try and compare the predictions of economic theory about the firm's motives for undertaking R and D with those of alternative theories of the firm.

There were several subsidiary reasons for undertaking this study which derive from the author's careful introduction to, and growing interest in, Bayesian and subjective probability methods as a result of a year's fellowship in the School of Business in Chicago in 1965-66.(5)

Once the decision to work in R and D was made much thought was directed towards how the study should be conducted. As a result of the author's literature search and discussion with a few self-selected research engineers, it became clear that the only way to understand the dynamics of a complex mechanism such as R and D was to carry out depth or case studies of the decision process at the firm level. Such a method by its very nature has faults.

For example, the firms who co-operated were simply those who were sufficiently interested in the work to undertake a fairly severe commitment of time - as such the sample has no general validity whatsoever. The trade-off for such an approach is clearly the ability to concentrate on depth rather than breadth of coverage, i.e., to sacrifice generality for insight.

Within the firms who co-operated, the work was carried out in three broad stages:-

(i) An attempt to understand the meaning of R and D to the firm. The work here sought to find out about the organisation, finance and management of R and D and to try and isolate the interactions and feedback mechanisms linking R and D activity to the firm as a whole and to other sub-functions within the firm.

(ii) An attempt to carry out a thorough and detailed analysis of previous historical projects carried out by the R and D activity. This retrospective analysis helps to throw light upon the research areas and interests of the firm, the factors taken into account in deciding upon particular projects and the degree to which firms are effective in the research area.

(iii) An attempt to construct and evaluate models for helping the decision-maker to analyse prospective projects for inclusion in the R and D program.

Of these three stages (i) and (ii) are the descriptive, analytical material on the decision process and (iii) is the normative material. The first two stages rely heavily on the research method and this point will be taken up in detail in the relevant sections. The third stage is the really difficult one in which trade-offs of realism against computational convenience inevitably have to be made.

The way in which this thesis is organised closely follows the logic of the organisation of the study. The aim has been to provide a logical flow in the argument section by section. To achieve this the material is organised in five parts as follows:

a) Part I:- THE CONTEXT OF THE PROBLEM

The evaluation of the economic evidence on R and D at the firm level and a questioning of the predictions of the classical economic theory of the firm.

b) Part II:- THE QUESTIONNAIRE STUDY

The first stage in the R and D decision analysis, i.e., how decisions are made within the firms analysed.

c) Part III:- THE RETROSPECTIVE STUDY

The second stage in the decision analysis, i.e. the effectiveness of the firms in their past completed R and D work.

d) Part IV:- THE MODEL-BUILDING PHASE

The third stage in the decision analysis, i.e., the attempt to formalise quantitatively how decisions are made and to use rational models to put forward "normative" aims.

e) Part V:- SUGGESTIONS FOR FURTHER WORK AND CONCLUSIONS

Areas not touched upon by the existing work - directions in which further research should be concentrated.

It is traditional in theses to include literature surveys early on in the thesis. Here, because we have decided to divide the text into five parts following the distinct phases of the work, we shall prefer to present literature surveys for each of the parts in turn whenever they are applicable. In this way the reader should be able to appreciate the logic of the work much more clearly and thus be kept in touch with the argument step by step. The only exception to this is at the beginning where we analyse a fair proportion of studies in order to provide a realistic justification for studies of R and D at the micro level.

Finally, it is customary to complete the introductory statement of intent by summarising the planned aims of the work. First, to understand the nature of R and D. Second, to present a detailed analysis of the decision process in R and D. Third, to build models of an operationally useful nature (if possible) given a thorough knowledge of the decision process. Fourth, to speculate on the usefulness of "normative" theories of statistical decision.

It will be clear at the end whether we have succeeded in fulfilling the task. The only judge in this context must be the reader, if he is satisfied and has gained insight then the task will have been worthwhile.

Chapter I

THE ECONOMIC EVIDENCE ON THE ECONOMICS OF RESEARCH AND DEVELOPMENT

1.0 Introduction

The aim of this chapter is to provide a broad overview of the published literature on the economics of science. The range of contributions is so wide and diverse that it is necessary to have a framework within which to survey the published work. The suggested framework has three broad divisions and sub-topics within these as follows:- [1 (a), (b), (c)]

1. THEORY OF INVENTION AND INNOVATION

   including problems of the definition and measurement of inventive activity.

2. MACRO-ANALYSES

   1. The effect of research and development on the country's rate of economic growth.
   2. The impact of non market factors such as government science policy measures on R & D activity.
   3. International comparative studies on R & D activity at the national and industry levels.

3. MICRO-ANALYSES

   1. The analysis of the sources of inventions.
   2. The diffusion of innovations.

3. The effects of market structure on R & D activity at the firm and industry level.

4. The effect of R & D activity upon the productivity and profits of the firm and industry i.e. the payoff aspects of research and development.

5. The definition and measurement of the output of research and development.

6. Case studies of particular development projects and innovations.

7. The management of research and development within the firm.

It must be noted that the subject categories are not mutually exclusive and that the references cited are not intended to be a comprehensive list but to indicate the directions in which research has progressed. In this section economic theory and its applications are emphasised whilst other references remain for more detailed consideration in succeeding parts.

1.1. THE THEORY OF INVENTION AND INNOVATION

The main motivation for the development of the theory of innovation has been the impact of technological change. Studies[2,3,4], carried out in relation to the American economy have shown that only a small fraction of increased output/worker in

America over the last 100 years or so can be explained by increased capital per worker. The remainder can be attributed to increased efficiency - a component of which must be the process of technical change which produces new techniques for manufacturing existing products and evolves totally new products. The existence of this phenomenon of technicalchange has made economists aware of the need to examine the basic relations between invention and economic activity.

A subsidiary reason for the renewed interest of economists in the links between research and economic activity has been the increasing awareness* that many corporations involved in the competitive process may concentrate their competitive effort on the development of new products and processes rather than on price manipulation. Firms are seeking long-term growth as a major objective and foregoing short-term optimality. In a sense pareto-optimality is being sacrificed for a longer-term optimality based on the addition of new products.

Whatever the reason for the interest in technical change in order to build a theory economists need to understand the processes involved in inventive activity. It is widely accepted that it is useful to distinguish between INVENTION AND INNOVATION [5]. An invention can be thought of as the output of the process of inventive activity. The output may be a new production process, product or something more fundamental. The process of innovation is concerned

---

* See, for example, Baumol, W. J. Economic Theory and Operations Analysis. Englewood Cliffs, N. J.: Prentice Hall, 1963.

with the commercial exploitation of the results of the inventive process.

There is disagreement about the determinants of invention and the speed of response of innovation to invention. Schumpeter[6], who perhaps first formulated the distinction between invention and innovation, suggests that inventions are an exogenous stimulus to the economic system and regards the decision to innovate as the province of the entrepreneur. If such a view is accepted then it implies that inventions occur randomly and are not an outcome of increased economic activity. This tradition of the exogeneity of technical change is a basic reason why the relations between invention and economic activity are relatively unexplored.

Schmookler[7] in some very important work is largely responsible for calling into question the Schumpeterian treatment of invention as an exogenous variable. He addresses himself to the problem of whether inventive activity influences economic activity or is influenced by it. There are, of course, valid instances of the exogeneity of invention such as the constant drive of the pure researcher acting to improve the stock of technical knowledge. Such instances are not at issue. The main issue is whether technical change is mainly endogenous or exogenous.

From a detailed analysis of patent data and of significant historical innovations Schmookler concludes that in general inventive activity in a field tends very much to fluctuate with economic activity in that field. In particular, he finds that investment leads inventive activity. This result is against the Schumpeterian view and also the well-known work of Salter[8].

As a result of Schmookler's lead most economists working in the area of invention have tried to integrate inventive activity into the framework of conventional economic analysis. Schmookler's own later work[9] is an example of this type of development.

Nordhaus[10] attempts to develop an economic theory of technological change. He contends that an adequate micro-theory of the generation and transmission of new knowledge is necessary in order that a reasonable model of the inventive process can be developed and tested. He builds on the work of Schmookler, Arrow[11] and Jewkes[12] who have stressed that inventive activity is always an uncertain undertaking and that inventive inputs (R & D) and outputs (inventions) are qualitatively different from productive inputs and outputs in the classical economic analysis of production.

The distinctive character of research activity unearthed by the previous authors leads Nordhaus to suggest that a sophisticated model of the research process is necessary. The work of Solow mentioned previously, which was a great advance in the field of productivity measurement, would suggest that inventive activity should be treated as a productive input in the production function in the same way as capital. Nordhaus rejects this approach and regards the capital theoretic productivity work of Grilliches and

Jorgenson[13] and Lucas[14] as being too crude because of the treatment of inventions as a capital good without regard to the distinctive character of the inventive input. In this rejection he is supported by Arrow[15] who suggests that production function models may be useful descriptively but they do not capture the essential features of the creation and transmission of knowledge.

The novelty of Nordhaus's approach is his treatment of invention. He assumes that inventions are produced within the system and are defined as either new processes of production or new vectors of input-output coefficients. He regards any invention as being potentially a public good either because it is indivisible or can be used universally at zero marginal cost. However, he recognises the intervention of safeguards, legal or otherwise, to provide a temporary monopoly on the results of the invention. The inventor is granted a temporary monopoly over his work during which time he can produce output or license his work. After the safeguarded period the research work is open to exploitation by any one. This approach differs from Schumpeter's conception of the entrepreneurs reaping the benefit from the exploitation of a given invention. Nordhaus assigns the innovation decision to the inventor who thus obtains the profits or surplus of entrepreneurial activity.

Having otherwise made neo classical assumptions about the economy (other than in the sphere of knowledge production) Nordhaus goes on to devise tests of the relation first between inventive activity and the growth of productivity and second between inventive activity and economic activity based on a production function type analysis. The first test is unsuccessful and the problem of isolating this relation remains to be solved. Sanders[16] in an earlier study was equally unsuccessful. The second test gives a positive result and is consistent with Schmookler's earlier findings on the endogeneity of technical change.

Much remains to be done in the area. The problem of measuring inventive activity is a difficult one. Nordhaus in his study follows Schmookler by using numbers of patents as his indicator of inventive activity. This indicator is deficient because there may be differences in the behaviour of industries and firms within industries in their desire to patent. In using patent data there is also the bias arising from quality differentials between patents. Some weighting scheme to measure patent worth is clearly necessary to overcome the biases involved in assigning equal weighting to both trivial and complex patents.

Arrow and Nordhaus both make a case for the distinctive character of research. Arrow regards research and development as being connected with the problems of uncertainty reduction. Each step in the progress of technological change adds knowledge and tends to reduce the residual uncertainty. Each step in producing knowledge is qualitatively different from each other step. Logically, therefore, knowledge production is different from each production of physical goods where successive items can be qualitatively identical. It is clear that Domar[17] agrees with both of them in their desire to move towards models for the analysis of technical change in which proper allowance is made for the micro-character of the inventive process. The whole literature evidence on the subject[18] (see the NBER volume for the broad coverage of the area) brings out the micro nature of the processes of technical change and the need to bring in concepts from other disciplines to understand them and point to directions for further research.

The theory of innovation is thus developing slowly. Most economists believe that economic activity provides the main but not the sole stimulus for the development of inventive activity. Schumpeter's position is not now held by many. Given the link between invention and economic activity work is now being directed towards a more sophistivated view of the processes of invention in the hope of providing more fruitful models of the economic and productive value of invention. This point will be further developed as one of the main themes of Chapter 3.

1.2 MACRO-ANALYSES

1.2.1 R & D AND THE RATE OF ECONOMIC GROWTH

The economic history evidence of Abramovitz and Schmookler showed the inability of the increase in the capital/labour ratio to explain the major part of the increase in per capita income in the U.S. The rate of technical change was thus suggested as being one of the elements that would account for most of residual unexplained variation. Similar conclusions were derived by Denison[19], Fabricant[20] and Massell[21] in their corresponding econometric history studies.

Schmookler's[22] later work points to a demand-induced or market theory of inventive activity in which the two most important determinants of the supply curve of inventions in a given area are taken to be the number of suitably qualified people and the present state of knowledge in that area.

Some more recent work has been carried out by Minasian[23] and Mansfield[24] to try and measure the effect of R & D expenditure on a firm or industry's rate of technical change. The measurement of technical change is derived from Solow's[25] work (which involves the addition of an extra trend term to reflect technical change in a production function analysis) and both authors provide some results on the magnitude of the rate of technical change.

Much remains to be done if the exact nature of the relations between R & D and economic growth is to be determined. The studies reported offer little information on the amount a country should spend on R & D and virtually none on how the overall global R & D budget should be distributed amongst the industrial sector of the economy. For a policy-maker four questions need detailed answers[26]: first, what is the relative productivity of the various types of unit in which R & D is carried out? What appears to be the most efficient R & D unit in terms of size and organisation structure? Second, given the optimum allocation of R & D to the most efficient R & D sub-units, what is the nature of the relation between total R & D expenditure and the rate of technical change? Third, given that the links between R & D and rate of technical change are know, what is the broader effect of R & D on economic growth? Fourth, how do we decide upon the optimum combinations of input factors such as investment, R & D expenditure etc. in order to achieve the objective of a given rate of economic growth?

To achieve the answers to these questions it is clear that we need to know much more about the research and development process at the micro level. Little is known about the nature of R & D work in various industries and the extent to which the composition of a firm's R & D portfolio affects its rate of technical change. Once more is known about research and development within the typical industrial firm more information will be available on the extent to which technical change in a firm requires investment in new capital equipment and its effect on the firm in terms of saving amounts of alternative productive factors, capital and labour.

Most growth models assume that the effect of technical change is neutral. Fellner[27] suggests that there is some evidence to show that the effects of technical change are not neutral and feels that rough estimates of the extent of capital or labour saving should always be calculated. It can be seen, therefore, that more detailed micro-information about the nature of R & D will improve the treatment of R & D input in growth models and help to establish empirically the relation between R & D and growth on a sounder theoretical basis.

1.2.2. THE IMPACT OF NON-MARKET FACTORS ON R & D ACTIVITY

Nelson[28] makes the point that in the United States a fairly large proportion of research is government controlled. He notes that on the demand side over half the demand is federal government investment and on the supply side the universities and government laboratories figure prominently. Shanks[29] brings this statistical picture up to date and states that three-fifths of all R & D in the U.S. is government financed. The greater proportion of U.S. government finance is spent on defence and aerospace programmes. Because the financial support is directed largely towards a few key programmes the U.S. government has been eager to make sure that there is a spin-off from these programmes to the civilian sector of the economy. Programmes such as Polaris have aided the development of PERT[30] techniques in research planning and such techniques have since been widely adopted. Shanks[31] outlines the mechanisms by which the U.S. government tries to help "spin-off". He concludes that there is still very little evidence that the massive investment in space technology by the United States will produce an adquate commercial pay-off. This technology transfer from key programmes to industrial R & D is limited to some extent by the mutual distrust between Federal Government and Industry.

In Britain on the other hand government and industry cooperate more readily. There are a number of government sponsored institutes and research associations and a considerable involvement by the Ministry of Technology and the National Research Development Corporation in the sponsorship of research. In Britain as in the United States the greater proportion of research and development work is government financed or sponsored. The greatest support areas are those related to defence and weapons systems. Very little work has, however, been done on the effectiveness of such expenditures and on determining at what level government sponsorship should stabilise. Such benefit /cost analyses of government expenditures are clearly necessary.

A valuable adjunct to cost/benefit studies of government R & D expenditures are case studies of the effectiveness of particular research programmes. Marschak[32, 33] presents evidence of the effectiveness of certain defence projects and his work clearly shows the groping and uncertain nature of research activity.

Perhaps the most useful example of a case study in the British context is the work of Grossfield and Heath[34]. Grossfield and Heath looked at the case of the potato harvester, the development of which was aided by financial support from the National Research Development Corporation and the National Institute of Agricultural Engineering. A related study in the American literature is the analysis by Grilliches[35] of the research costs and social returns of hybrid corn and other related innovations. The important feature of both studies is their attempt at measurement of the social returns of the innovation.

Cost benefit analysis is in its infancy and requires much research on the measurement of costs and benefits. Its development is important in the government context as a check on the effectiveness of sponsorship.

1.2.3. INTERNATIONAL COMPARATIVE STUDIES OF R & D AT NATIONAL AND INDUSTRY LEVELS.

Perhaps the most thorough and detailed work in this area has been pioneered by C. Freeman[36, 37, 38, 39, 40] and his associates at the National Institute of Economic and Social Research. Such work is of value to national policy makers because it provides guidelines with which to judge the relative effectiveness of national R & D efforts and the strength of several key industries, for example, plastics, electronics and chemical process plant, in international competition.

As of 1962 Freeman[41] finds that expenditure on R & D as a proportion of national income is running at 3.1% in the U.S., 2.5 - 3% in the U.S.S.R. and 1.6% in Western Europe. The corresponding proportions of the labour force employed on R & D work are found to be 6.2%, 4.4% and 2.9% respectively. At official exchange rates the U.S. spends four times as much as Western Europe and about 3-4 times as much as the U.S.S.R. on research and development. When these figures are calculated in real terms allowing for factor cost differences U.S. investment in R & D is 2.5 times that of Western Europe and 1.2 times that of the U.S.S.R.

These figures help to place the R & D effort of the various countries in context but on their own they do not explain the large gap between the United States and Europe in terms of R & D effectiveness. Many hypotheses for the greater effectiveness of U.S. R & D can be offered. Shanks[42], for example, suggests that the more hard-headed commercial attitude of American firms and the size and scale of the large American corporations may be responsible for U.S. leadership.

Freeman's[43] industry studies are part of a programme of studies designed to discover the relationships between research, innovation and market performance of the principal firms in various industries namely plastics, electronics and chemical process plant. One of the uses Freeman makes of patent statistics is to analyse the performance of the technical leaders in these

Industries and he finds, for example, that leaders were ahead in numbers of innovations, patents taken out and volume of R & D inputs. In plastics the dominance of Germany in technical leadership and production over both Britain and the U.S. is attributed to the initial leadership achieved by I.G. Farben Ltd. between 1931-45 when Farben spent a great deal more than any other firm on R & D and produced twice as many patents. Despite a resurgence of U.S. and British research (mainly I.C.I.) in the early fifties, the leadership of German R & D was reasserted largely because of the German tradition and history of excellence in plastics research giving Germany something that could loosely be described as "research economics of scale in plastics."

Chemical process plant work is found to be dominated by the U.S. firms. Not only do U.S. firms win the greater proportion of large contracts but their design and development work is regarded as superior to the competition. Freeman attributes this to the close interaction in the U.S. between the plant construction companies and their clients - the oil and chemical companies. In America companies release a constant flow of process innovations to contractors and work closely with them in design and development work. In this way the lead time between process invention and innovation and adoption is considerably minimised.

Some work by Brechling and Surrey[44] and Dhrymes[45] on the electricity utility industry has shown the different approaches adopted in the U.S. and U.K. on the design of electricity generation equipment. The CEGB in the U.K. has an avuncular attitude to the construction companies and as a virtual monopsonist handles the design work itself on the principle that it is more aware of the characteristics and performance required from new equipment. This divorce of design from production is not present in the U.S. where electric utility companies are privately owned. Westinghouse and General Electric, for example, have design teams integrated, coordinated and controlled by the producer and the production team. Whether or not design control from outside affects the creativity and output of the British producer is a testable hypothesis as the performance results of the industries in both countries are readily available.

It is clear that the studies pioneered systematically by Freeman analyse closely the structure of individual indistries and analyse the reasons for success and failure in the context of that industrial environment. If the lessons of failure are learnt and acted upon, then the government support of newer industries should incorporate the lessons from previous experience. The value of such studies is two-fold:- first, to emphasise the need for the constant revision and revaluation of industrial strength. Second, to make the administrator aware of the process of learning from experience in doing research work. Some of the guidelines from the chemical process plant study should have helped firms in that industry in the U.K. to encourage their clients to work with them and feed them research results quickly so as to maintain their competitive position.

Freeman's work has been widely used by Martin J. Peck[46] in a detailed study of the economics of science and technology in Britain. The study is an applied macro economic analysis drawing upon Freeman's work, national statistics on science and technology and various government reports on scientific activity[47]. Peck makes two hypotheses which he tries to verify. First, that Britain is trying to do more with its science and technology than manpower resources permit. He illustrates the truth of this hypothesis by comparing the ratio of total R & D expenditures to GNP with the ratio of scientists and engineers as a percentage of employment for the major industrial countries. These figures show that Britain is spending half as much again as the U.S. on R & D, relative to GNP, but with a much smaller proportion of technically qualified personnel. As Peck points out this may simply say that Britain is very efficient in the use of scientific manpower or that other countries are under-committed in R & D. The figures quoted show that Britain suffers from a relative shortage of engineers and has, therefore, to incur costs of substitution by employing trained scientists or technicians (HNC level) in place of engineers. Furthermore, Britain overall has a far smaller relative percentage of qualified scientists and engineers working in industry. This shortage of scientists and engineers in industry coupled with an industrial structure in which research intensive industries are relatively more important than elsewhere lends further weight to the overcommittment hypothesis since this cohort of scientists and engineers has also to service a large defence and basic research effort.

The hypothesis is not fully proven. Proper allowance has not been made for the influence of the technical college trained engineer and his relatively greater importance to the British firm. Peck is not able to offer evidence on how many of the qualified technicians would have a similar level of competence to some American engineers. A study of the comparability of qualifications between countries would point to a more useful definition of the term engineer. It is clear that the outcome of such a study would be to include at least a part of the qualified technicians under the category engineer.

If the effect of the technician were large then relative disparities between countries in the proportion of technically qualified personnel would narrow and reduce the substitution effect predominantly to the scientist/engineer substitution.

The relatively greater proportion of scientists employed in industry in R & D in Britain together with the relatively smaller proportion of engineers employed in industry compared with other OECD countries can be considered to be evidence of a substitution of engineer by scientist. On the other hand the relative difference could equally well be caused by either or both of:

(i) a preference by firms in their employment policies for scientists over engineers because of the greater technical flexibility of the former (and thus their ability to learn an engineering role on the job)

(ii) an awareness by firms that engineering training is not a homogenous commodity. Some schools keep abreast of industrial needs and technical developments in their course planning but others have a very limited and narrow training. Of an entrant has been to a poor department, the firm has to incur a cost of training in making the new entrant aware of the techniques and methods most useful to the firm. The firm might consider that it would be preferable to incur the same level of training cost on a more technically flexible scientist than a less flexible, narrowly trained engineer.

Second, Peck establishes the second hypothesis in his study without questioning its validity. He comments[48] that it is said that British managers of R & D decide on projects without adequate allowance for marketability cost and production considerations and that execution of projects lacks the sense of urgency necessary for timely completion, ie. that economic management of R & D lacks understanding of economic factors and their relation to time. Without pointing to the source of these remarks he comments that they are consistent with the overcommittment hypothesis as the available engineers have not sufficient free time given the relatively greater pressure of work to analyse the economic characteristics of a project. Shanks[49] notices a distinct difference in the attitude towards R & D by British and American firms. The Americans he feels are aware of their objectives for doing R & D and are aware of the effect of

R & D on profitability and growth. He develops this point further by noting the control and evaluation procedures that exist for R & D in American industry which are not paralleled in British industry. Shanks' observations lend support to the second hypothesis but the published research evidence to date doesn't. If we consider the evidence it is clear from the RAND studies[50] in the U. S. that although allowance is made in military R & D for cost, production and marketing factors the ability of the estimators to make accurate initial estimates is poor. In Britain the work of Allen[51] shows that for the seven projects he analysed allowance is made for economic factors but the initial estimates of these factors are also very inaccurate. In both cases the time slippage between estimated and actual time for completion is of the same order of magnitude.

Much more evidence needs to be gathered about the effectiveness of R & D management. A limited amount of case study evidence is given in later chapters but this alone is not sufficient to confirm or deny that effective economic management of R & D is purely the preserve of American industry.

Peck in his analysis concludes that he has established beyond resonable doubt the validity of his hypotheses about British over-committment to R & D. He may be right but there are points that need to be considered before accepting the analysis. His conclusions are based on an analysis of aggregate statistics which require careful interpretation. Peck's analysis is sound in so far as it goes but it suffers from the one major deficiency, namely, that Peck was not able to draw on depth analysis at the micro level to validate some of his statements. It certainly raises the question of how much Britain can afford to spend on R & D? It cannot answer this question without more detailed micro-work to enrich the aggregate analysis.

In the next major section we turn our attention to some representative examples of research work published about the economics of R & D at the firm (or industry) level.

1.3. MICRO-ANALYSES

1.3.1. The Analysis of the sources of inventions

No question is more interesting in this area than the nature of the inventor. Who is he and under what conditions does he achieve maximum inventive output? Jewkes, Sawers and Stillerman[52] in the most comprehensive work on major twentieth century inventions find that less than half the inventions are the direct result of company or firm research. Their evidence points to the strong influence of the individual inventor but in recent years patent analyses have shown the increasing influence of firms in applications for patentable inventions.

Schmookler's evidence[53] of a random sample of patents taken out in the U.S. in 1953 shows that about 1/3 of them are the result of the activities of the individual independent inventor, the remaining 2/3 receiving either part or full company or government sponsorship.

An invention may turn out to be economically viable at a given point of time. Why do successful inventions occur more at certain points in time than others? We know that inventions respond to economic activity so it is not surprising to find from the work of Grilliches and Schmookler[54] that the investment rate in an industry tends to lead the patent rate. Schmookler[55] has also found that patent activity in an industry has a positive high correlation with the output and investment in that industry. This suggests that patent activity will tend to be related to the business cycle, a suggestion that is supported by the work of Graue[56].

In summary, invention is a response in the main to economic factors. Although the "pioneer myth" of the amateur inventor still exists the greater proportion of inventive output results from the full-time employed inventor.

1. 3. 2. The Diffusion of Innovations

Innovation is considered to be the process by which inventive output i. e. knowledge or information is commercially exploited. Given that an invention is commercially adopted, what is the process by which the knowledge about this innovation, be it a new product or process, is transmitted through the economic system? This process of knowledge transmission has attracted the attention of both economists and sociologists. The economist stresses the nature of the demand for innovation whereas the sociologist looks at the channels or processes by which information is transmitted from the inventor to the person interested in adopting the innovation. Arrow[57] summarises the approaches and indicates that the economic studies of Grilliches [58] and Mansfield[59] tend to emphasise the profitability of the investment and the risks involved. For example, Mansfield's interests in his diffusion studies are to determine the speed of adoption of the innovation and the most innovative type of firm. In his work he finds that if the profitability of the innovation and the size of investment required are held constant, the rate of imitation tends to be greater in less concentrated industries. Later research[60] carried out in the tool and die industry has tended to support Mansfields findings on imitation.

Sociologists, such as Coleman[61] and Rogers[62] have found out that personal contact is the most useful channel between adopters of an innovation and potential followers. Though mass media tend to have some usefulness they have greater cost elements and do not produce as many contacts. Arrow likens the sociologist's interest in the process of diffusion to studying the supply of different communication channels which have different cost elements attached to them. Coleman points out, for example, that personal contacts are not randomly distributed in the population and thus the manner in which an item is diffused throughout the system is correspondingly altered. Arrow cites one example, namely, the diffusion of use of new drugs was higher among physicians practising in pairs than among those practising singly.

It can be seen that hypotheses have been generated from existing research about reasons for the adoption of innovations and the processes by which knowledge about innovations diffuses through the economic system. More research is needed as the available economic evidence suggests that international inequalities in productivity and income have their origin in the relative efficiencies of the systems of information communication within those countries; i.e. some countries are apparently much better both at reducing the time lag between invention and innovation and at rapidly adopting a given innovation.

1.3.3. Effects of Market Structure on R & D Activity at the Firm and Industry Level

Technical change increases the set of factor possibilities open to the firm in its production operations. It also increases the range of choice open to consumers in their purchasing decisions. Unfortunately, technical change costs money and economic resources must be allocated to R & D. As the firm is now the major unit from which inventive output is developed it is important to understand the relationship between an industry's market structure and its rate of technical progress. For example, do certain types of market structures encourage technical change and other inhibit technical change? There is no definite agreement amongst economists on the ways in which firm size and market structure affect the rate of technical change. In order to evaluate the literature on the subject it is instructive to consider what the theory of the firm has to say about the incentives to innovate under different market structures[63]. The key issue is clearly how much market organisation affects the rate of inventive activity.

Under both monopoly and perfect competition there is an incentive to reduce costs throughinnovation given an objective of profit maximisation. The distinction between the two cases lies in the long run incentive. A monopolist can always increase his profits through cost reduction and since by definition entry into the industry is barred these profits are maintained in the long run. The firm in a perfectly competitive industry has the same incentive as the monopolist in the short run but not in the long run. If the firm concerned is earning short-run profits it will attract entry of other firms by virtue of making greater than "normal" profit[64]. Clearly, therefore, the short run profits will be eroded through entry of new firms in the long run. Therefore, whether or not the incentive to innovate is sufficiently attractive to the firm in perfect competition depends upon the length of the short run period and the amount of "supernormal" profit. Obviously, the shorter the period the less willing will the firm in a competitive industry be to incur the costs of developing the new innovation.

Schumpeter[65] is the economist around whom the counter arguments to perfect competition centre. He feels it is unjustified to act "on the principle that big business should be made to work as the respective industry would work in perfect competition". He argues that profit incentives lead entrepreneurs to innovate and that monopoly power is an important instrument in providing the climate for the innovation process. Galbraith[66] supports Schumpeter's position and argues that an industry comprising a few large firms will do more R & D than one with a large number of small firms because larger firms have more financial resources available to them and can trade off research expenses against tax laws.

There are an equally large number of economists who take the opposite view that although the incentive to innovate is greater in monopolistic conditions there may be less pressure to do research because of the absence of competition. The argument can be developed to show that the more competitive the conditions the stronger the incentive to innovate in order to maintain one's market position. A strong competitive position now may result in bankruptcy later unless research results are constantly used to produce new products or processes.

The evidence available does not conclusively point to an optimum type of industrial structure for industrial innovation. The evidence on the monopoly side comes from Maclaurin[67], Villard[68,69] and Nelson[70]. Maclaurin adopts a subjective approach in which he assesses the degree of monopoly and rate of technological progress in thirteen selected American industries. The tables he presents, based on subjective judgment and not objective definitions, show that there is a strong association between monopolistic conditions and the rate of technical change in industrial situations. In discussing his results he states that although some degree of monopoly is necessary for technical progress it must be associated with elements of competitive conditions which themselves stimulate progress. Villard has collected data on research and development expenditures as a proportion of sales for various sizes of firms in six different American industries. His evidence shows that in three of the six industries there is an increasing percentage spent on R & D as we progress from smaller to larger firms. This is not conclusive and his only useful result is the fact that in five of the six industries the largest firm spent the highest percentages on research and development. This rather weak relationship suggests that oligopolies promote greater research and development expenditures. Nelson's case is a more theoretical one and is essentially that the larger size of an oligopolistic firm allows it to use research results, wait longer for the payoff because of its corporate security and recapture a larger portion of the aggregate social gains from the research.

Schmookler[71] takes issue with Villard's interpretation of his data and suggests that above some minimum firm size there is no evidence of a relationship between R & D as a proportion of sales and firm size across the industries quoted. In this statement he is supported by evidence from the work of Jewkes[72] and Nutter[73].

Indeed Mansfield[74] in some more recent work has shown that for the industries for which he had data, the largest firms spent a somewhat smaller proportion of their sales on R & D than did smaller rivals.

Hamberg[75] in a review article sums up the position on market structure very well. He states that though a positive association between R & D intensity (i. e. percentage of sales devoted to research and development expenditure) and industrial concentration apparently exists, it must be described as weak, as must also be the case for industrial concentration as a stimulus to R & D, both in absolute and relative terms. Scherer[76] in a later article concludes that little support can be mustered for the hypothesis that corporate bigness, conglomerateness, and market power are especially favourable to technological progress.

It could well be that different market structures suit different industries for their R & D needs. Fuchs's[77] work on the economics of the fur industry tends to support the hypothesis that oligopoly conditions are conducive to the promotion of technological change. He finds that the major technological changes in the industry have been initiated by the breeders and tanners which are sectors of the fur market with a fairly oligopolistic structure. Comanor[78] on the other hand finds that for the pharmaceutical industry there is a significant interaction between research and firm size, and increasing firm size tends to be associated with a decline in the productivity of the research. He suggests that at least for the pharmaceutical industry doubt must be cast on the view that extensive research establishments within large firms are necessarily an efficient means of fostering an accelerated rate of technical advance.

It can be seen that the evidence on R & D by industry is such that we have no method of predicting the type of competitive structure most conducive for effective research and development activity in a given industry. More work is needed at the individual industry level before any general analysis can be made. Comanor's article does raise one interesting related question. Is there any evidence of economies of scale in R & D? His conclusions for the pharmaceutical industry indicate that within relatively small firms there are substantial economies of scale in R & D but that when firm size becomes even moderately large decreasing returns to scale become evident. Mansfield[79] provides some very tentative evidence regarding the extent of economies of scale in the chemical, petroleum refining, and steel industries. He confirms Comanor's result that the productivity of a firm's R & D declines as the size of firm increases, holding the size of R & D expenditures constant. As Mansfield[80] states elsewhere most economists would agree that there are economies of scale in R & D up to some point. There would, however, be disagreement about the extent of such economies and the critical size of research establishment. Both examples given above indicate that the critical size will vary from industry to industry depending on the amount of capital equipment necessary to operate an an effective research laboratory.

Another question that is of interest is whether certain large firms, small firms or government establishments produce a more significant flow of inventions than others? The answer to this question depends on how we define an invention. If we are strict and say that it is unique in character or of strategic importance to the nation then the available evidence indicates that the market place is not the environment in which the major inventions are produced. Hamberg[81] finds that, with few exceptions, the large industrial research laboratories are minor sources of major inventions. In fact, industrial laboratories are likely to be major sources of essentially improvement inventions. Although his findings are based on only 7 studies, Hamberg suggests that for economic and organisational reasons they are likely to be generally true.

McConnell and Peterson[82] present evidence on R & D activity in small firms (defined to be firms which employ less than 500 people). In this category all research work is found to be of an applied improvement or new product type and it can safely be concluded that small firms do not produce significant inventions.

It seems clear that if the firms adhere to their own objectives they will do R & D for profitability considerations and thus carry out product improvement research. Pure Invention research seems to be the preserve of universities and government financed contract research. The influence of the space programme and various defence programmes in the U.S. upon the creation of a flow of significant inventions has been enormous.[83] Risk capital for such programmes provides "spin-off" to civilian R & D, a process which Professor E. Roberts has described in a recent seminar.[84]

Given that the major inventions tend to be produced outside the market place it is interesting to discover whether certain market structures are more conducive to the speedy commercial introduction of new products and processes derived from the output of the inventive process. Mansfields[85] study is perhaps the most authoritative in this area. He finds that in some industries the largest firms account for a disproportionately large share of the innovations but in others they do not. He suggests that the effect of market structures on the speedy commercial generation of new innovations is dependent upon the size of investment required to innovate and other related economic factors. His evidence suggests that the positions of Bain[86] and Brozen[87], who extol the Virtues of competitive conditions in generating innovations and Villard[88] who favours oligopoly as a stimulant to speedy innovations, are like those of extreme right or left wing politicians viz. their arguments hold in some cases but not in others. Much research needs to be done in this area but it will not be surprising if Mansfield's results are confirmed.

A related topic of interest is the influence of market structure on the process of diffusion of an innovation through an industry given that the innovation is adopted by some unit within the industry. Mansfield's [89, 90, 91, 92] work is again the most authoritative. The main findings are as follows. First, the greater the number of firms in an industry using a new technique the more likely is it that the remainder will follow. Second, the rate of diffusion in an industry tends to be higher for more profitable innovations, for those requiring smaller levels of investment, and for those utilising existing capital equipment. The rate of diffusion is not constant across industry, there being no definite tendency for degree of concentration to affect rate of diffusion. The diffusion rate in an industry tends to be higher when its output is growing rapidly. Third, there is no consistent pattern to suggest that certain firms are innovation leaders in given industies. Fourth, the speed of adoption of a new innovation by a particular firm is a function of its size and the expected profitability resulting from adoption of an innovation. Fifth, small firms seem to be quicker in adapting themselves to new techniques and processes than older ones do.

Further research in this area needs to follow the leads suggested by Arrow in a previous section. More fruitful models of the diffusion process need to be constructed using the basic work of Mansfield and others in sociology. In this way we will understand better how to promote conditions which favour the rapid and efficient adoption of the available technology.

It can be seen from this review of evidence on the effect of market structure on R & D that it is not yet clear if particular market structures encourage R & D activity. As such it is too early to say whether market structure is an external economy to the individual firm in its quest for R & D profitability.

1.3.4. The Effect of R & D Activity on the Productivity and Profits of the Firm and Industry

The final aim of R & D activity is the production of a flow of innovations. The value of this flow must be measured in relation to the extent to which each element of the flow achieves particular stated objectives. It is clear that R & D at the firm level has commercial objectives which in the end can be summarised by the desire to increase profitability. The aim of developing new or improved production processes is to reduce the costs side of the profit equation whereas the aim from new product growth is to increase sales and market share and hence the revenue side of the equation. A subsidiary objective of new product introduction is the desire to maintain long term growth.

It is necessary to differentiate between the firm and the industry in measuring the effect of new innovations because benefits accruing to the individual firm and industry may be different. At the firm level there is in theory a great amount of accounting and other information available for ex post evaluation of the benefits accruing from a new innovation. Ex ante there may be information available from historical projects on costs/benefits etc., but if Peck's[93] point is true, in Britain R & D personnel are not aware of cost/ benefit considerations in commissioning and undertaking innovative research. In theory, of course, ex ante evaluation could be carried out. There are according to Nelson[94] many problems in such work. The case study evidence[95] in the N. B. E. R. volume suggests that quite a detailed and sophisticated analysis is required to understand where profit opportunities lie - if we assume that inventive effort is motivated by profit maximisation considerations. Two sets of factors are regarded as being important in the perception of profit opportunities in invention viz. organisational and economic factors. Rubenstein[96, 97] emphasises the importance of such organisational factors as the distribution of power and influence in the company; the relations between functional areas in the firm (e.g. marketing and research); The communication channels[98] available to the researcher in his search for ideas and information and the composition and research specialities of the research team. The economic factors are outlined by Nelson. We must be able to determine which factor costs are important to the profits from innovation. We must also be able to assess whether firms try to estimate the demand for innovation and the supply curve for innovation of that type in their innovation decisions. Further, we must have information on whether new innovations require new investment in capital equipment i. e. are innovation and investment in plant and equipment complementary goods?

Schnee[99] is at present working on the determinants of development costs in the drug industry and his preliminary findings quoted by Mansfield[100] indicate the significant variables. If studies such as these highlight the most significant cost influences, information will be available from which we can proceed via sensitivity analysis or a similar approach to isolate the relative influence of the significant cost variables on the expected profit criterion. This type of approach is known in chemical engineering as risk or venture analysis and will be discussed in detail in Part IV of this thesis.

Ex ante evaluation can in principle, therefore, be carried out. As this thesis proceeds some of the available methods will be outlined and compared. Even though such cost benefit analyses can be attempted, very few studies of innovations at either the firm or industry level have been published. The approaches of Grilliches[101] and Grossfield and Heath[102] were attempts to assess the benefit to the community, farmers and manufacturers of new innovations viz hybrid corn and the potato harvester. In both cases great difficulty was encountered in trying to measure social benefits.

At the industry level the effect of a new innovation requires a different type of analysis from a detailed within firm evaluation of profit opportunities.

At this level attempts must be made to assess the possible external benefits and costs that might accrue from widespread adoption of the innovation throughout the industry. Again, a great research effort is needed here because of the existing state of knowledge.

The main reasons for the absence of cost benefit studies from the literature can be attributed to any or all of the following reasons:[103]

(i) the difficulty of selecting, isolating and measuring the appropriate "costs" and "benefits". This is clear from Griliches, Grossfield and Mansfield's work.[104]

(ii) the unwillingness of firms to allow researchers to scrutinise past records.

(iii) the desire to maintain company security in a competitive research environment.

If the measurement of the effect of R & D on profitability is beset with measurement problems so also is the effect of R & D on productivity. One of the main complications is the uncertainty about the relation between R & D and capital investment. If R & D and capital investment are complements in the inventive process it becomes impossible to distinguish between the effects of each in a Cobb-Douglas production function type analysis. Most of the work in this area has been contributed by Minassian[105, 106] and Mansfield[107]. Minassian views R & D activity as representing efforts to increase efficiency. In his early work he considers the relationship between the rate of growth of productivity and research and development expenditures and finds a positive correlation. His later work is an analysis of the rate of return to R & D expenditures measured by a production function type analysis. Although he doubts the value of Cobb-Douglas production functions he uses the Cobb-Douglas framework and a covariance analysis to measure rate of return. For a sample of seventeen firms in the chemical industry he calculates estimates from log regression results of the elasticity of capital and research and development expenditures and uses these with estimates of the average real value added (the Cobb-Douglas output variable) per firm per year, average real gross capital per firm per year and average real accumulated R & D expenditures to estimate the marginal products for capital and R & D expenditures. From these he estimates that the gross return on investment in R & D is 54% compared with 9% for capital. Despite his lack of faith in the production function type analysis he is fairly confident about the accuracy of his estimates even though they depend upon the form of production function assumed.

Mansfield attempts to construct a simple econometric model to estimate the marginal rate of return from R & D expenditures in various firms and industries. Provided we assume a production function of Cobb-Douglas form with capital, labour and total past R & D expenditures as inputs simple expressions can be obtained for the marginal rate of return from R & D given the further necessary assumption that R & D expenditures have grown at an exponential rate. These expressions remain simple no matter whether technical change is capital-embodied or organisational. "If technical change is capital embodied, the marginal rate of return is directly related to the elasticity of output with respect to total past R & D expenditures and the rate of investment but inversely related to the ratio of total past R & D expenditures to present output".

On the basis of the theoretical results he attempts to estimate the marginal rates of return in 1960 for ten major chemical and petroleum firms and lower bounds for the marginal rate of return for ten manufacturing industries. For individual industries the rate of return was very high in petroleum ; in chemicals it was high for capital embodied technical change and low for organisational technical change. The rate of return was directly related to a firm's size in chemicals and inversely related to it in petroleum. For the industry data the rate of return on R & D is highest in the food, apparel and furniture industries.

It is fair to say that Mansfield and Minassian's work is by no means definitive. The defects of Cobb-Douglas work are well known[108] and the simplifying assumptions particularly the neutrality of technical change are unrealistic. The major defect of the work is the attempt to fit the unique character of R & D process into the classical economic input/output mould without sufficient justification.

It is very clear that major research effort needs to be directed towards the pay off aspects of R & D and later in this thesis some ex post and ex ante evaluation of R & D profitability is presented.

1.3.5. Definition and Measurement of the Output of R & D Activity

One problem remains in any analysis of the payoff from research and development and that is how we define the output from R & D activity. We have seen earlier that the intermediate output of the R & D process is a flow of knowledge or inventions which become a flow of innovations provided in each case an entrepreneur commercialises the results of the inventive process.

Freeman[109] has recently written a review paper on the measurement of the output of research and development activity. In his discussion he disposes of those people who argue that it is impossible to measure the output of R & D activity[110]. He emphasises that the task is difficult but if we consider a model of the inventive process in which inventions and innovations are the flow of output certain features of the output flow are well known. Parts of research activity are channeled into patent applications and the learned journals and, provided certain difficulties in interpretation, such as differences in the quality of this output, are allowed for, we can in principle measure the output of this portion of research activity. Yet the most interesting portion of research and development activity is the output of enterprise-level R & D which is rarely the subject of patent application or learned paper submission. In these cases measurement has to be indirect and heavily dependent upon the cooperation of individual firms. Methods such as cost-benefit analysis, both *ex ante* and *ex post*, of innovations can prove to be relevant measurement tools. The rationale of cost/benefit analysis is, given the cost of innovation, what is the estimated or actual benefit that will occur to the firm. The principles underlying this method have been outlined in the pay off section and some results are presented later in the thesis for a small sample of commercial R & D projects.

There is no doubt that detailed case study research, industry by industry and project by project, will enable the output of micro level commercial research to be better understood. Only in this way can the relation of firm to industry and generalisations about output at the industry level be attempted.

1.3.6. Case Studies of Particular Development Projects and Innovations

In the previous section it is suggested that a case study approach is valuable in providing guide lines by which micro level R & D can be better understood and measured. The drawbacks of the case study approach are primarily that the firms or cases studied may be a biased sample. Firms who co-operate tend to be atypical and not representative of the cross section. As such generalising from case studies to conclusions about industry wide behaviour is often pointless. The researcher is definitely faced with a considerable dilemma in this area but it is sensible to do research with the cooperative firms and not wait for an utopian environment where company security is not endangered.

There are many examples in the literature of case study approaches. Four important pieces of work are singled out here; first, the NBER work of Mueller[111], Enos[112], Peck[113], Marschak[114] and Nelson[115]; second the work of Jewkes[116], Sawers and Stillerman; third the work of Mansfield[117] and fourth, the work of J. A. Allen[118]. Mueller, Enos and Peck's work can be considered together as an attempt to describe the history of technological change and invention in various industries. Enos, for example, gives some interesting information on the innovating firms in the petroleum industry. Marschak and Nelson describe in great detail the development of a new communications system for Bell Telephone Laboratories and the basis transistor. Their interest was more in finding out the reasons for development and the time path of the innovation process. Marschak for example, finds that the communications system development was rational and had as its main objective cost reduction.

Jewkes et al have performed perhaps the basic work in analysing the sources of major twentieth century inventions. Their findings summarised earlier stressed the importance of the individual inventor in stimulating the inventive process.

Mansfield's case study is an attempt to describe first of all the mechanisms by which a given laboratory appraised potential research and development projects. Having understood the mechanisms he sought to build and test descriptive models of the project selection process. From a case study point of view the presentation of the formal system for project appraisal used in the firm gives useful guide lines for further work in this area without laying any claims to generality.

Allen is a professor of Chemistry who has adopted the daunting course of following a series of major innovations through from the pre-invention stage right to the point of full scale production. He tries to dwell at length on the total situation of these innovations both in depth and breadth and consider both economic aspects and scientific and technological issues. He adopts the viewpoint of the historian and attempts to incorporate in the analysis any relevant factors connected with the industrial and scientific pre-history of the innovation. The innovations he studied were polythene, terylene and oxygen steelmaking. Some further work on the history of innovations is currently in progress at the Science Policy Research Unit in Sussex University.

Case study work must figure more prominently in future research output. The value of such concentrated depth research is in the insight given into the relevant economic and scientific factors in particular innovations. From the model building point of view case studies can help to unearth some of the key economic and technical factors in commercial research and development activity.

1. 3. 7. The Management of Research and Development within The Firm

One of the favourite topics of the popular management journals[119] has been how to manage scientific research effort within the firm. The literature is almost 100% normative and as Mansfield[120] says is almost completely devoid of scientific content.

From the management point of view the work of Klein and Meckling[121] is extremely important. They suggest that inventive activity is a form of problem solving and as such is characterised by a considerable degree of uncertainty and unpredictability. This evidence on the groping, sequential nature of the R & D process and its unpredictability does not favour a predictive theory of inventive activity. However, subsequent evidence suggests that uncertainty in R & D is very great initially but diminishes greatly through time[122] and this provides a rationale for the development of useful predictive theories.

The most important economic problems facing an R & D manager are first, how to appraise ex ante the worth of a given flow of potential areas of R & D activity or projects. Second, given a worth assessment how to determine the optimal distribution of resources amongst the set of projects which possess probabilistic outcomes. Third, given an optimal allocation at some point in time how to review and control the performance of the selected portfolio of projects.

The literature on these problems will be evaluated in detail later.

For now, a brief summary of approaches will be given. The measures of worth suggested for R & D projects vary from numerical indices[123] to capital budgeting criteria such as the DCF rate of return[124].

Many possible strategies for managing R & D efforts have been presented. One of the most plausible is the concept of parallel inventive efforts. Klein[125] argues that the type of uncertainty inherent in R & D implies that decision makers might be wise to run several R & D efforts for a particular project in parallel. The rationale for this approach is that, since uncertainty about the outcome of a given configuration of R & D effort is highest initially, if a number of possible effort configurations (or approaches) are carried on in parallel, the passage of time will allow us to decide upon the optimal approach. Other approaches to project selection are based upon models borrowed from the mathematical programming literature and are summarised by Baker and Pound[126]. However, it must be said that there is sparse published evidence on the application of these approaches and this tends to imply that they have not yet gained wide acceptance.

One of the favourite tools suggested in the literature for the control of R & D programmes is PERT. This was initially developed as an offshoot of the POLARIS programme in the United States and has since gained rapid adoption. Evidence presented by De Paula in a recent publication suggests that PERT is not widely used for project control in the United Kingdom.

1.4. Summary

In this chapter much evidence has been evaluated and the field as a whole reviewed. The economic literature has been emphasised and topics taken up and referred to later in the thesis are mentioned only in broad outline.

In the review of the literature it can be said that the area is one in which it is difficult to see the wood for the trees. In places, evidence conflicts sometimes because of poor data and at other times because of definitional difficulties. It is clear that much more research is needed and indications of the most important areas are given. Also, the areas in which this thesis will present evidence are outlined.

One point that emerges forcefully from the literature is the strikingly micro-character of R & D activity. Arrow is right when he says that we have to move towards more fruitful theories of the inventive process. To this end the next chapter investigates the usefulness of the micro economic theory of the firm in providing a base for a theory of the inventive process and evaluates the extent to which organisational concepts and other theories such as learning theory and statistical decision theory help towards the construction of a more operationally useful theory of the firm.

Bibliography

1. For alternative literature summaries see

   a) E Mansfield, "Economics of Research and Development" in Patents and Progress (ed. V. Terpstra): New York, John Wiley, 1965

   b) R. R. Nelson editorial in R.R. Nelson (ed), The Rate and Direction of Inventive Activity, Princeton: Princeton Univ. Press, 1962

   c) E. Mansfield, Economics of Technological Change: New York, W. W. Norton, 1968

2. J. Schmookler, "The Changing Efficiency of the American Economy, 1869 - 1934", RES, August 1952.

3. R. Solow, "Technical Change and the Aggregate Production Function", RES, 1957.

4. M. Abramovitz, "Research and Output Trends in the U.S. since 1870", AER, 1956.

5. See for example R. D. G. Lipsey, An Introduction to Positive Economics, London: Weidenfeld and Nicholson, 1967.

6. J. Schumpeter, The Theory of Economic Development, Harvard, 1934.

7. J. Schmookler, "Changes in Industry and the State of Knowledge as Determinants of Industrial Invention" in R. R. Nelson (ed) Rate and Direction of Inventive Activity, Princeton for NBER, 1962

N.B. RES stands for Review of Economics and Statistics
AER stands for American Economic Review
NBER stands for National Bureau of Economic Research

8. E. G. Salter, Productivity and Technical Change, Cambridge, 1960.

9. J. Schmookler, Invention and Economic Growth, Harvard, 1966.

10. W. D. Nordhaus, "An Economic Theory of Technological Change", AER, Papers and Proceedings, May 1969, pp. 18-29.

11. K. J. Arrow, "Economic Welfare and the Allocation of Resources" essay in NELSON, Rate and Direction of Inventive Activity, Princeton, 1962.

12. J. Jewkes, D. Sawers and R. Stillerman, The Sources of Invention, London: MacMillan & Co. Ltd., 1962.

13. Z. Grilliches and D. W. Jorgenson, "The Explanation of Productivity Change", Review of Economic Studies, July 1967, pp 249-83.

14. R. E. Lucas, "Tests of a Capital Theoretic Model of Technical Change" Review of Economic Studies, Sept. 1967, pp 21-37.

15. K. J. Arrow, "Classificatory Notes on the Production and Transmission of Technological Knowledge" AER, Papers and Proceedings, May 1969, pp 29-36.

16. B. S. Sanders, "Some Difficulties in Measuring Inventive Activity", in "Rate and Direction of Inventive Activity" NBER 1962.

17. E. D. Domar, "Discussion to Papers on the Theory of Innovation", AER, May 1969, p. 44.

18. R. R. Nelson (ed), The Rate and Direction of Inventive Activity, (Princeton) 1962

19. E. Denison, The Source of Economic Growth, 1962.

20. S. Fabricant, Basic Facts on Productivity Change, Princeton, 1959

21. B. Massel, "Capital Formation and Technological Change in U.S. Manufacturing" RES, 1960.

22. J. Schmookler, 'Determinants of Inventive Activity," AER, 1962.

23. J. Minasian, "The Economics of Research and Development", in the Rate and Direction of Inventive Activity, (Princeton) 1962.

24. E. Mansfield, Econometric St udies of Industrial Research and Technological Innovation, New York: W. W. Norton, 1966.

25. R. Solow, op cit. RES, 1957.

26. See E. Mansfield Economics of Research and Development" p. 109 in Terpstra (ed), Patents and Progress, J. Wiley, 1965.

27. W. Fellner, "Does the Market Direct the Relative Factor-Saving Effects of Technical Progress" in R. R. Nelson (ed), The Rate and Direction of Inventive Activity, Princeton for NBER, 1962.

28. R. R. Nelson (ed), editorial commentary in Rate and Direction of Inventive Activity, Princeton, 1962.

29. M. Shanks, The Innovators, (Penguin, 1967) p. 79

30. See K. Lockyer, An Introduction to Critical Path Analysis, London: Pitman, 1966.

31. M. Shanks, op cit. (see pp. 80-82)

32. T. Marschak, in The Rate and Direction of Inventive Activity, Princeton, 1962.

33. T. Marschak et al, Strategy for R & D, Berlin: Springer-Verlag, 1967.

34. K. Grossfield and J. B. Heath, "The Benefit and Cost of Government Support for R & D: A Case Study", Economic Journal, September 1966, pp 537-49

35. Z. Grilliches, "Hybrid Corn, An Exploration in the Economics of Technological Change", Econometrica: October 1957.

36. C. Freeman and A Young, The R & D Effort in Western Europe, North America and the Soviet Union, OECD, 1962

37. C. Freeman, " R & D, A Comparison between British and American Industry, NIESR, 1962

38. C. Freeman, "The Plastics Industry - A Comparative Study of Research and Innovation", NIESR, 1963.

39. C. Freeman, "Research and Development in Electronic Capital Goods", NIESR, 1965.

40. C. Freeman, "Chemical Process Plant, Innovation and the World Market", NIESR, 1968.

41. C. Freeman, see reference 36.

42. M. Shanks op cit., (29)

43. C. Freeman op cit (37, 38, 39, 40)

44. F. P. R. Brechling and A. J. Surrey, "An International Comparison of Production Techniques: The Coal Fired Electricity Generating Industry", NIESR, 1966.

45. P. J. Dhrymes & M. Kurz, "Technology and Scale in Electricity Generation", Econometrica, July 1964.

N.B. NIESR stands for National Institute of Economic and Social Research Review

OECD stands for Organisation for European Community Development, Paris.

46. M. J. Peck, "Science and Technology" Chapter 10 in Britain's Economic Prospects, ed. by R. E. Caves: London, Allen and Unwin, 1968.

47. A full analysis of the available statistics in science and technology is presented later in the thesis.

48. M. J. Peck, op cit - p 448, in Caves (ed), Britain's Economic Prospects, Allen and Unwin, 1968.

49. M. Shanks op cit. (29)

50. See for example Marshall and Meckling, in NBER volume ed by R. R. Nelson, Rate and Direction of Inventive Activity: Princeton for NBER, 1962.

51. D. H. Allen & P. J. November, "A Practical Study of the Accuracy of Forecasts in Novel Projects, Symposium on Technological Forecasting, Institute of Chemical Engineers, November 1968.

52. J. Jewkes, D. Sawers and R. Stillerman, The Sources of Invention, London: MacMillan & Co. Ltd., 1958

53. J. Schmookler, "Inventors Past and Present" RES, 1957.

54. J. Grilliches and J. Schmookler, "Inventing and Maximising" AER, 1963.

55. J. Schmookler, "Changes in Industry and State of Knowledge as Determinants of Industrial Invention" in NBER volume Rate and Direction of Inventive Activity, Princeton, 1962.

56. E. Graue, "Inventions and Production", RES, 1943.

57. K. J. Arrow, "Classificatory Notes on the Production and Transmission of Technological Knowledge" AER, Papers and Proceedings, May 1969.

58. Z. Grilliches, "Hybrid Corn, An Exploration in the Economics of Technological Change", Econometrica, October 1957.

59. E. Mansfield, Econometric Studies of Industrial Research and Technological Innovation, New York: W. W. Norton, 1968.

60. E. Mansfield, "Numerical Control in the Tool and Die Industry, The Diffusion of a Major Technological Innovation", unpublished paper, 1968.

61. J. S. Coleman, Introduction to Mathematical Sociology, Free Press, 1964

62. E. Rogers, The Diffusion of Innovations, Free Press 1962

63. See for example, R. G. D. Lipsey, An Introduction to Positive Economics, London: Weidenfeld and Nicholson, 1967.

64. Normal profit is the situation where the firm is covering its costs which include a %age mark-up for normal profit.

65. See J. Schumpeter, The Theory of Economic Development, Harvard, 1934.

66. J. Galbraith, American Capitalism, Houghton, Miffin, Boston.

67. W. R. Maclaurin, "Technological Progress in Some American Industries", AER, Papers and Proceedings, 1954.

68. H. H. Villard, "Compaetition, Oligopoly and Research", Journal of Pol. Economy, 1958.

69. H. H. Villard, "Reply", Journal of Pol. Economy, 1959

70. R. Nelson, "The Simple Economics of Basic Scientific Research," Journal of Pol. Economy, 1959.

71. J. Schmookler, "Bigness, Fewness and Research", Journal of Pol. Economy, 1959.

72. J. Jewkes et al. Sources of Invention op cit

73. O. Nutter, "Monopoly, Bigness and Progress", Journal of Pol. Economy, 1959.

74. E. Mansfield, "Industrial Research Expenditures: Determinants, Prospects and Relation to Size of Firm and Inventive Output", Journal of Pol. Economy, August 1964.

75. D. Hamberg, "Size of Firm, Oligopoly and Research: The Evidence", Canadian Journal of Economics and Political Science, February 1964.

76. F. M Scherer, "Firm Size, Market Structure, Opportunity and the Output of Patented Innovations", AER, December 1965.

77. V. R. Fuchs, The Economics of the Fur Industry, Columbia University Press, 1957.

78. W. S. Comanor, "Research and Technical Change in the Pharmaceutical Industry", RES, May 1965.

79. E. Mansfield, "Industrial Research Expenditures; Determinants, Prospects and Relation to Size of Firm and Inventive Output", Journal of Pol. Economy, August, 1964.

80. E. Mansfield, "Economics of Research and Development", p. 117 in Terpstra (ed), Patents and Progress, New York: J. Wiley, 1965.

81. D. Hamberg, "Invention in the Industrial Research Laboratory," Journal of Political Economy, April 1965.

82. C. McConnell, "R & D : Some Evidence for Small Firms", Southern Economic Journal, April 1965.

83. See M. Shanks, op cit (29)

84. E. Roberts, seminar on the MIT Science Project to the research seminar in social sciences, Faculty of Social Sciences, Edinburgh, 1967.

85. E. Mansfield, "Size of Firm, Market Structure, and Innovation", Journal of Pol. Economy, December 1963.

86. J. Bain, Pricing, Distribution and Employment, New York: Holt Rinehart & Winston, 1953

87. Y. Brozen, "Invention, Innovation and Imitation" AER, 1951

88. H. Villard, "Competition Oligopoly and Research", Journal of Pol. Economy, December, 1958.

89. E. Mansfield, "Technical Change and the Rate of Imitation", Econometrica, 1961

90. E. Mansfield, "The Speed of Response of Firms to New Techniques", Quarterly Journal of Economics, 1963.

91. E. Mansfield , "Intrafirm Rates of Diffusion of an Innovation, Review of Economics and Statistics, 1963

92. E. Mansfield "Diffusion of Results of R & D", p. 137 in Terpstra (ed), Patents and Progress, New York: J. Wiley, 1965.

93. M. J. Peck, "Science and Technology" in R. E. Caves (ed) Britain's Economic Prospects, London: Allen and Unwin, 1968.

94. R. R. Nelson ed, Rate and Direction of Inventive Activity, Princeton, 1962

95. See the papers of Enos, Schmookler, Peck and Marschak as examples in Nelson (ed), Rate and Direction of Inventive Activity, Princeton, 1962.

96. A. H. Rubenstein, "Studies of Project Selection Behaviour in Industry" in Dean (ed), Operations Research in Research and Development, New York: J. Wiley, 1963.

97. A. H. Rubenstein, "Organisation and Research and Development Decision Making Within the Decentralized Firm", in Nelson (ed) The Rate and Direction of Inventive Activity, Princeton, 1962.

98. D. B. Hertz and A. H. Rubenstein, "Team Research", Dept. of Industrial Engineering, Columbia University, June 1953.

99. J. Schnee, "Costs of Development" doctoral dissertation forthcoming, University of Pennsylvania.

100. E. Mansfield, "Industrial R & D: Characteristics, Costs and Diffusion of Results, AER, May 1969 p. 69, Papers and Proceedings.

101. Z. Grilliches, op cit. Econometrica, 1957.

102. K. Grossfield and J. R. Heath, op. cit. Economic Journal, 1966.

103. C. Freeman, "Measurement of the Output of R & D" UNESCO, 1969 p. 30.

104. E. Mansfield, Econometric Studies of Industrial Research and Technological Innovation, New York, W. W. Norton, 1968.

105. J. R. Minasian, "Economics of R & D", in R. R. Nelson (ed), Rate and Direction of Inventive Activity , Princeton, 1962.

106. J. R. Minasian, "R & D, Production Functions and Rates of Return, AER, May 1969.

107. E. Mansfield, Econometric Studies of Industrial Research and Technological Innovation, New York: W. W. Norton, 1968.

108. See Solow op cit and also Machlup's paper in the NBER volume op cit. on the problems of fitting invention into a production function format.

109. C. Freeman, "The Measurement of the Output of Research and Development", UNESCO, 1969.

110. See for example F. Machlup, in Rate and Direction of Inventive Activity, Princeton, 1962.

111. W. Mueller, "The Origins of the Basic Inventions Underlying Du Pont's Major Product and Process Innovations, 1920-1950" in Nelson (ed) op cit.

112. J. Enos, "Invention and Innovation in the Petroleum Refining Industry" in Nelson (ed) op cit.

113. M. J. Peck, "Inventions in the Postwar American Aluminium Industry" in R. R. Nelson (ed) op cit.

N. B. UNESCO stands for United Nations Educational, Scientific and Cultural Organisation.

114. T. Marschak, "Strategy and Organisation in a System Development Project", in R. R. Nelson (ed) op cit.

115. R. Nelson, "The Case of the Transistor" in R. R. Nelson (ed) op cit.

116. J. Jewkes, D. Sawers and R. Stillerman, The Sources of Invention, Macmillan, 1962.

117. E. Mansfield and R. Brandenburg, "The Allocation, Characteristics and Outcome of a Firm's R. & D Portfolio", Journal of Business, October 1966.

118. J. A. Allen, Studies in Innovation in the Steel and Chemical Industries, Manchester University Press, 1968.

119. See for example The Harvard Business Review.

120. E. Mansfield, "Economics of Research and Development" in Terpstra (ed), Patents and Progress, New York: John Wiley, 1965.

121. B. Klein and W. Meckling, "Applications of O. R. to Development Decisions", Operations Research, May 1958.

122. See for example R. R. Nelson, "Uncertainty, Learning and the Economics of Parallel R & D Efforts", RES, November 1961.

123. See A. Hart in "Symposium on Productivity in Research." Institute of Chemical Engineers, 1963.

124. A. J. Merrett and A. Sykes, Capital Budgeting and Company Finance, Harlow: Longmans Green, 1967.

125. B. Klein, "The Decision Making Problem in Development" in Nelson (ed) Rate and Direction of Inventive Activity, Princeton, 1962.

126. W. R. Baker and W. H. Pound, "R & D Project Selection: Where we Stand" I. E. E. E. Transactions on Engineering Management, 1964.

Chapter 2

TOWARDS A MODEL OF THE INVENTIVE PROCESS WITH SPECIAL REFERENCE TO DECISION MAKING

2.0. Introduction

In this chapter we will try to analyse the usefulness of classical economic theory as a model for the inventive process. The discussion will use existing evidence and will seek to incorporate the known characteristics of technologically progressive firms and of the inventive processes within firms into a more realistic model of the inventive process. In the discussion a recent article by W. Z. Hirsch[1] will be used as the framework for our analysis.

We shall consider first what we know about technologically progressive firms and the process of invention. We shall therefore, outline the distinctive features of the inventive process and the economic problems faced by the decision maker in promoting R & D activity. Once the problems faced by the R & D decision maker are clear we shall then try to assess the value of economic theory. Finally, we shall review other models which have been suggested for the analysis of decision processes.

2.1. The Characteristics of Technically Progressive Firms

It is clear that there are many characteristics of technologically progressive firms, which require theoretical insight and explanation.

---

1. W. Z. Hirsch, "Technological Progress and Microeconomic Theory", AER, Papers and Proceedings, May 1969.

First, by what procedures do these firms determine their research policy? Have they a series of objectives which they seek to satisfy or is the assumption of research for reasons of profit maximisation a reasonable simplification? Second, why do certain industries have a monopoly of the technically innovative firms? Third, do large firms have economies of scale in R & D? Fourth, does advertising have an effect on technical progress?

The answers to these questions and others are not yet available. However, we can at least point out some of the distinctive features of technically progressive firms.

One of the most important issues in the development of models to explain the economics of R & D is the identification of the individuals in the firm who make policy decisions about R & D. Such major policy decisions include the determination of a total budget for R & D work and the allocation of this budget amongst different projects. The neoclassical theory of the firm assumes that there is a single decision maker in the firm, the entrepreneur, who both owns and manages the firm's resources. The entrepreneur is assumed to be motivated by profitability considerations in his decision making process and the costs of his decision making are only material if the direct consequences of decisions turn out to be unprofitable.

Is it realistic, therefore, to suggest that a single decision maker assumption is sufficient for the description of economic decision making in R & D? There is an abundance of information in the management journals[2] suggesting how R & D activities ought to be organised in order to maximise research output. Burns and Stalker[3] find that various types of organisation structure have been adopted for innovation management but a feature of most of them, apart from the pyramidal type structure, is the decentralization of decision making for R & D from the entrepreneur-owner level to a technical manager whose function is to coordinate research activity in his area. Further, the entrepreneur-owner level rarely consists of a single decision maker except in the very small firms. E. B. Roberts[4] in his studies of research offshoots from the Lincoln Laboratory and the MIT research park area has found that small contract research firms tend to have a single entrepreneur owner in whom complete authority for management and decision making is vested. In small firms, therefore, the assumptions of neo-classical theory are approximately satisfied but in large firms there is considerable decentralisation of authority and more evidence of group decision making. Hirsch finds two variants of the neo classical assumptions in the literature. First, Henderson and Quandt[5] view the entrepreneur as an engineer manager who chooses the optimal production function and manipulates output and price in order to maximise profits. Second, Friedman[6] treats the entrepreneur as the resource owner who does not sell the rights to use his resources in production to someone else. The reward for entre-

2. See for example, the Harvard Business Review, R & D Management Series
3. T. Burns and G. M. Stalker, The Management of Innovation, London: Tavistock
4. E. B. Roberts, "Paper on MIT Science Project", Faculty of Social Sciences, Edinburgh, 1967.
5. J. M. Henderson & R. M. Quandt, Microeconomic Theory, McGraw-Hill, 1958.
6. M. Friedman, Price Theory, Aldine, 1962.

preneurship is the residual between revenue for the product and the cost of producing the product (which includes opportunity cost elements on behalf of the owner).

Hirsch[7] suggests that a more useful concept of the entrepreneurial function is to divide the role of the entrepreneur into two parts which correspond to the practice of decentralised decision making. The entrepreneur-owner maintains the risk bearing function but delegates a lesser entrepreneurial role of routine decision making to a tachnical manager. The reward of the entrepreneur-owner for risk bearing is profit defined as capital gains or losses in the value of ownership rights plus the differences between dividend receipts and the riskless opportunity rate of return on the owner's investment. The reward to the technical manager consists of his sanctioned income which is a function of the profit to the entrepreneur and unsanctioned income derived from discretionary use of the firm's resources as a result of authority delegation. Such discretionary use may reduce entrepreneur profit and hence sanctioned income. It is worthwhile to replace a manager if and only if the loss resulting from his discretionary use is greater than the costs of the owner "policing" the manager.

For all these reasons Hirsch suggests that the reward structure within firms sometimes leads to technical decisions which do not maximize profit to the owner because of a manager's

---

7. This is based on R. Teeples, "A Working Paper on the Theory of the Firm" UCLA, 1968.

concern for his own job. He further suggests that differences between R & D expenditures in large and small firms can be accounted for by the differences in managerial complexity between these types of organisation.

Even if a model in the R & D area makes satisfactory allowance for decentralised and group decision making, several other issues must be resolved. How do firms gain access to sources of finance for promoting R & D activity? How do they decide upon suitable production methods and determine the expected demand for a new product? Are any cost/benefit assessments made ex ante?

Hirsch[8] points out that a primary difference between firms in their capability to undertake R & D lies in their relative ability to finance R & D. The literature survey in Chapter concluded that the case for bigness and scale in R & D activity has not yet been settled but that there was evidence of scale effects in a number of industries depending upon the nature of the product offered. Hirsch has been more selective in his literature review and asserts that significant scale economies exist for R & D activity especially for the kinds of product and production technique associated with technically progressive firms. He quotes an article by Baldwin[9] which supports his assertion that large firms appear to have an advantage in securing economies of large-scale R & D activities.

---

8. W. Z. Hirsch, op cit., p. 41

9. W. L. Baldwin, "Contracted Research and The Case for Big Business" JPE, June 1962.

Having demonstrated the truth of his assertion in this way he points out the advantages that large firms have for exploiting large scale R & D. Some of the advantages are the low cost of capital of R & D activity to the entrepreneur and low transactions and communications costs between technical personnel and management at least up to a given firm size. Though these advantages do exist Hirsch is too eager to generalise about bigness.

The neoclassical theory of the firm disregards scale effects in R & D activity. Both the size of firm and its scale of activity in R & D are considered to be irrelevant and unimportant. It is clear that the positions of Hirsch and the neoclassival theorists are both extreme and the truth lies somewhere between them. Studies must be undertaken in the area of financing in R & D to determine the constraints on the level of budgets for R & D in industry, the extent of internal financing of R & D, the relative importance of extraform risk bearing agencies, and the financial characteristics of projects that receive allocations from the R & D budgets. Such considerations must be included in any realistic model of the financing element of the inventive process.

When resources have been allocated to projects a proportion of them eventually lead to research output. A question that Hirsch poses is with whom are the property rights to the invention vested. If the output is specific to the firm then the increased knowledge is transmitted within the firm. However, inventive knowledge most often has value to competing firms and an inventor within the firm can seek job offers at a higher salary and in a sense the profit from the inventive knowledge is gained by the research worker. A further problem that faces the firm is that technical knowledge is implanted in the intellect of its research staff which is the possession of those staff. In order to increase the stock of technical knowledge embodied in the collective intellect of its staff the firm can choose between policies designed on the one hand to retain the experienced research man or on the other hand to have thorough training programmes to train relatively less experienced people. Both alternatives incur costs and the firm must make a choice between them and a range of other possible alternatives.

Of course, if the research output is the subject for a patent then the property rights are vested in the patentee for a specific term. During this period he may hinder the adoption of new techniques if he decides to carry out the process of production himself without selling his patent rights through licences or royalty agreements. In practice, patent rights are often bartered on the open market and infringed in large firms in the knowledge that patent lawyers will be able to work some sort of trade off between patents vested in each firm or make a financial settlement, Thus, neoclassical theory[10] is upheld at least for largish firms when it maintains that the principal obstructions to the employment of new techniques are the costs of obtaining information, switchover costs, and a reluctance to take risks.

---

10. W. Z. Hirsch, op cit. p. 41.

Given that the firm is in possession of research results it has to decide on the choice of production technique to exploit such results. The nature of technical progress is such that production techniques change with the passing of time in a dynamic manner and often the firm is not fully aware of the range of production possibilities open to it. Neoclassical theory assumes that the decision maker is fully aware of the set of possibilities and that there is contemporaneous transformation of inputs into outputs. Neither of these assumptions is fully realistic and such effects as learning[11] from experience in the production process and intertemporal trade-offs in production are neglected.

A most important issue in a model of the inventive process is how firms decide ex ante on the likely benefit to be gained from commercial adoption of a proposed new product. Often the market for the product is not known exactly and the firm is keen to find out the expected demand for the product under various marketing mix combinations i. e. at given levels of advertising expenditure and price. It is clear from case study evidence, for example in Part III of this thesis, that there is a relationship between the expected demand and the expected cost of a new product. If a firm is unable to complete the development work on a project in a given time, for whatever reason, it usually has to inject extra cost resources into the project in order to complete it within a reasonable time. The slippage of time and the extra resources involved in

---

11. See for example K. J. Arrow, "The Economic Implications of Learning by Doing", Review of Economic Studies, 1962.

ensuring as early a completion time as possible is costly. The delay in completion of the work means that at the point of commercial introduction the product may have to face increased competition. In some situations, therefore, there may be a relationship between a firm's demand curves and supply curves which should be analysed clearly.

The analysis has so far centred on the decision maker in R & D, the decisions he has to make, and the assumptions made by neoclassical theory. We have not discussed either the nature of the decision to undertake research and development work or the processes by which ideas for possible research projects are generated within the firm.

It has been fashionable to treat all business decisions as investment decisions under uncertainty. It is said that almost every major decision involves a cost element and is undertaken in order to provide some required pay off or return to the firm. Marketing decisions involve an investment in some firm of advertising medium in the hope of providing some extra increment of sales. Capital investment decisions likewise involve an investment in plant or equipment in the hope of an extra increment of productivity and thus extra return. Research and development is regarded by the theorist as being similar in nature to capital investment except that the investment is in new technical knowledge rather than new machinery. Therefore, in the search for useful models for assessing the worth of research and development projects a thorough consideration of the various approaches in the literature on capital budgeting can prove to be very worthwhile. This point is taken up in greater detail in Part IV.

The processes of idea generation in R & D within the firm are by no means widely understood. Studies that have been undertaken have not documented the process of idea generation and diffusion within the firm in anything like sufficient detail for model building purposes. The attention of sociologists[12] has been drawn towards the process of idea generation and their interest can only lead to a greater understanding of the mechanisms involved.

We have now discussed in broad outline some of the characteristics of research and development and the implications of these characteristics for the development of useful models of the decision mechanisms in the R & D process and thus for the process itself. The most quoted single theory of firm behaviour is the neoclassical theory of the firm. The next section considers its value as a building block for a model of the R & D process based on an analysis of decision making processes.

2.2. The Relevance of Neoclassical Theory to Model Building

In the consideration of any theory we must immediately draw the distinction between a descriptive[13] and a normative theory. A descriptive theory of the firm seeks to describe how the individual firm behaves, and given the observations of behaviour, predictions

---

12. See for example J. S. Coleman, Introduction to Mathematical Sociology, Free Press (1964)

13. See for example R. G. D. Lipsey, An Introduction to Positive Economics, London: Weidenfeld and Nicholson, 1967.

can be made about future behaviour. The normative theory suggests how firms "should" behave and is an attempt to provide the decision maker with methods to aid him in his decisions.

Criticising the economic theory of the firm has in recent years been one of the favourite topics of economists. This criticism is healthy but to be effective it must be shown that some aspect of the theory is disputed by carefully observed facts. We can never have an infinite amount of knowledge about hypotheses and we must adopt a statistical view in which we say that refutation or confirmation of hypotheses can never be final but that we must decide on the basis of the available evidence at a particular point in time.

The orientation of classical work in microeconomics has largely been normative. Economists[14] have been relatively uninterested in the behaviour of individual economic agents and have taken the view that they want to know how people <u>ought</u> to behave, not how they <u>do</u> behave.

The Marshallian Concept of the theory of firm describes the allocation of resources amongst firms in an industry, the long run development of that industry and its price structure. The theory is based on the concept of a competitive market, with atomistic decision making units, the firms, in which all transactions are accomplished by means of a smoothly functioning price mechanism.

---

14. See H. A. Simon, "Theories of Decision Making in Economics and Behavioural Science", <u>AER</u>, 49, pp. 235-83

In so far as any attention is paid to the internal structure of the firm, it is assumed to be centred around a rational decision maker - economic man - who possesses all relevant knowledge and who acts in a calculated manner so as to achieve an objective of profit maximisation. As can be seen there are many simplifications inherent in the theory which suggests that it will be of limited use to the study of decision making at the level of the firm given the known complexities of firms e.g. the organisation structure and the multiproduct nature of its operations. Classical theory has been extended to explain multiproduct firms and market situations where conditions of perfect competition do not exist. Its objective in these extensions is the same as in perfect competition, namely, to specify the mechanisms by which resources are allocated in the market place[15]. It is thus a theory constructed to explain in general terms the behaviour of firms in a given market and not the internal workings of a firm within that market. Any extension of the theory must, therefore, relate to its purpose and not some other imagined set of objectives.

Criticisms of the theory of the firm seem to follow the pattern pointed out by Bodenhorn[16]. First, that traditional theory makes incorrect assumptions; second, that it does not properly describe decision-making procedures within modern industrial firms and therefore, third, that it makes incorrect predictions about market behaviour of firms in the world.

---

15. G.P.E. Clarkson, Managerial Economics, Penguin, 1969. p. 53
16. Diran Bodenhorn, "A Note on the Theory of the Firm", Journal of Business, 1959.

Bodenhorn largely takes up Friedman's[17] position about the role of assumptions in the formulation and testing of theories. Friedman feels that a theory is developed to explain certain phenomena and that only the implications for these phenomena should be tested against reality. In particular, testing assumptions against reality is futile because they must be false. Freidman's test is, therefore, to accept a theory if its predictions conform with reality in the majority of cases. He concedes that the assumptions are an indirect test of the theory and this is interpreted by Bodenhorn to mean that we should consider the reasonableness of the assumptions as well as the accuracy of the predictions. If we adopt this view then Koopman's[18] position that both predictions and assumtions should be compared with reality to test a theory is partially taken into account.

Bodenhorn[19] goes further and states that on Friedman's definitions a theory is true with respect to the phenomena it correctly predicts. Classical economic theory may not be able to explain decision making theories within the firm but it is able to predict market behaviour. It is thus true with regard to its basic objective but its falsity in the explanation of the operation of decision making procedures within the firm means only that we need a new theory with a new set of assumptions to explain such procedures. It is a mistake also to view classical theory as a single theory; rather it is a set of theories which are able to explain

---

17. M. Friedman, Essays in Positive Economics, Chicago, 1943.
18. T. C. Koopmans, Three Essays on the State of Economic Science, McGraw-Hill, 1957.
19. D. Bodenhorn, op cit. p. 166.

some facets of market behaviour. The criticism that classical theory is of no use for explaining the decision process mechanisms within the "black box" - the firm - is true but not relevant because the objective of classical theory is the description of market behaviour.

It would obviously be useful to construct a decision process theory within the firm both from the point of view of understanding the system and constructing its interrelationships. As Bodenhorn points out[20] it does not follow that such a theory will necessarily help us in predicting market behaviour. It may simply be that we do not need to know how firms make decisions if we assume that they are all in the game to make money and will organise their internal procedures to achieve that objective.

The sum total of the argument is that even though economic theory is of no use in explaining decision process phenomena it must be judged by its ability to explain the classes of phenomena that it purports to explain. The justification for the development of theories of the decision process must come from Cohen[21].

"To achieve satisfactory answers to such questions as how are resources allocated within firms, what are the effects of organisation structure on entrepreneurial behaviour etc. we need to develop theories of the firm which incorporate a much greater degree of realism than does traditional neoclassical theory".

---

20. D. Bodenhorn, op cit. p. 168.

21. K. J. Cohen, "Simulation of the Firm" AER, May 1960.

The implied justification is thus that economic theory has left a number of largely unanswered questions which we must attempt to answer. To do so we must build on the very useful framework that the classical theory provides. It does not matter, therefore, that classical theory does not explain the distinctive character of the inventive process. We must use it as a major building block in the development of a more relevant theory of decision making in the inventive process.

Many economists have suggested revisions. In this next section we summarise some of the more important ones and review their value for our subsequent model building exercise.

2. 3. Suggested Revisions to the Theory of the Firm

We will not consider in this discussion the extent to which revisions to the theory provide a more useful theory of market behaviour. Our objective here is to move towards greater realism in theories of the inventive process.

Many researchers have pointed out the multiplicity o f objectives which firms seem to have. Drucker[22,23] suggests that firms seek to survive and to achieve this they require satisfactory performance in each of five areas. From Drucker's exhortations it is not possible to construct any theory with which we can try to predict the action a manager will take under a given set of circumstances. This is because Drucker always writes to provide a framework for good management

---

22. P. F. Drucker, The Practice of Management, New York: Harper and Row.
23. P. F. Drucker, "Business Objectives and Survival Needs: Notes on a Discipline of Business Enterprise", Journal of Business, 1958

but his writings are based both on inadequate preparation and understanding of the nature of a theory. In fact nowhere in Drucker's theory is there anything really new. We could take the position that the satisfactory attainment of five objectives could be achieved by maximising profits and in so doing performing satisfactorily according to four other criteria or objectives.

A much more weighty revision than Drucker's has been the work of the Carnegie School on the Behavioural Theory of the Firm. This theory specifically disaggregates the unit of interest in micro-economic theory from the market to the individual firm. Its objective is an analysis and prediction of a firm's decision making behaviour. In this theory of decision making behaviour the classical principle of maximisation is replaced by the notion of achieving a satisfactory level of performance. This satisficing objective is behind much of Drucker's work but the work of Margolis[24], Simon[25] and Cyert and March[26] provides attempts to lead towards an operational definition of the satisficing concept. Margolis tells us that a level of profits will be satisfactory if it earns the firm a return at least equal to its aspiration level. Nowhere in his analysis of decision making procedures is this aspiration level defined indeed the argument becomes almost circular when he asserts that the aspiration level equals or exceeds the satisfactory level. Thus, Margolis does not provide us with an operational definition of satisfactory profits. Simon suggests that the satisfactory profit level is a subjective concept

---

24. J. Margolis, "The Analysis of the Firm: Rationalism, Conventionalism and Behaviourism", Journal of Business, 1958.

25. H. A. Simon, Models of Man, Social and Rational, Wiley, 1957. See paper on "A Behavioural Model of Rational Choice"

26. R. M. Cyert and J. G. March, A Behavioural Theory of the Firm, Englewood Cliffs: Prentice-Hall, 1963.

for the manager concerned and varies in a dynamic manner with experience and time. The concept of satisficing adopted in the behavioural theory is defined in terms of levels of aspiration for performance on particular objectives and these levels vary through time. The theory allows for as many objectives as are highlighted by observations of firm behaviour. Each objective is regarded as a constraint on performance and satisfactory performance is evaluated with respect to the set of possible objectives. It can be seen , therefore, that the satisficing definition is somewhat woolly with subjective concepts such as aspiration levels to be measured. A relevant question to pose at this stage is "do the alternative theories based on assumptions of multiple objectives appear to be more useful than theories of decision making based on a single objective of profit maximisation?" The assumption of profit maximisation has intuitive appeal and though simplified can be justified as an approximation to the motivation of the individual firm. If it is the prediction of the behaviour of a single firm then a process involving the observation of firm behaviour, analysing the major objectives and providing operational measurement of these objectives is likely to be much more fruitful than an approach based on a simplistic assumption of profit maximisation. From a model building viewpoint the assumption of objectives should be left open and each case should be treated on its own observations of behaviour. It may well be that the multiplicity of goals thesis is merely a smoke screen to hide the real aim of the firm, namely, long run profit maximisation. If this is true, there is no virtue in complexity because we can treat attainment of sub-objectives as boundary conditions to the overall[27] aim of profit maximisation.

If we accept that it is more reasonable for a theory at the level of the individual firm to postulate multiple objectives we must ask whether the knowledge of those objectives is sufficient to enable us to predict behaviour. Cyert and March certainly believe that a knowledge of objectives together with the satisficing concept is sufficient to explain decisions within organisations. This view assumes that the employee accepts and acts towards the attainment of the stated objectives of the firms. There is evidence that managers adopt a strategy to further their own objectives first and those of a larger group be it the department or the firm as a whole to a much smaller extent: The onus is then on the firm to set up an organisation structure and control systems which bring the objectives of the manager and the firm into close proximity. An example of this type of approach is that of management by objectives[28].

Cyert and March's optimism about knowledge of objectives being sufficient to explain decisions within organisations is incorrest except under special conditions namely explaining repetitive decisions within a stable organisation.[29] The fact that managers in the firm have wide

---

27. See M. Shubik, "Approaches to the Study of the Decision Making Relevant to the Firm", Journal of Business, 1964, p. 110.

28. See for example J. D. Wickens, "Management by Objectives: An appraisal", Journal of Management Studies, October, 1965.

29. See Cyert and March, op. cit.

discretionary powers and freedom of choice raises several issues which face not only the behavioural theorists but also the decision theorists. Intuitively appealing though the satisficing concept may be it merely suggests a range of possible satisfactory solutions to the decision problem. It does not provide a decision rule for choosing within the range of possible solutions. Further, satisficing is a particularly difficult criterion to define operationally even if we accept its merit as the relevant objective for the firm. How can a thorough consideration of individual preferences and objectives be eliminated from the analysis? Yet Cyert and March feel that once the relevant satisficing set of objectives are known we are in a position to predict decision making behaviour. This assumes that an effective coalition exists between employee and employer in their joint perception of the value of the objectives of the firm and that procedures for efficient control and administration within the firm are implemented. This latter assumption is not materially different from the assumption that economists make to justify the fact that they can successfully predict market actions of firms without needing to know how the firms make decisions. Economists would say that firms are in business to make money and that they will, in general, set up administrative and other procedures to accomplish this objective.[30] Alchian[31] puts this in another way by saying that only those firms that set up efficient administrative procedures will survive.

---

30. D. Bodenhorn, op cit. p. 168

31. A. A. Alchian, "Uncertainty Evolution and Economic Theory". JPE, 1950

Cyert and March's theory really takes us a step further than Drucker's exhortations on how to organise the firm to achieve optimum performance. It provides an attempt to formalise and measure a behavioural theory and is a significant addition to the literature. Yet the number of applications of this formulation has been limited largely because of the necessity of undertaking a thorough and detailed analysis of a decision problem which is both time consuming and out of the mainstream of economic research at the moment. Clarkson's[32] doctoral thesis is an example of how a detailed study of the decision processes of a particular trust investment manager can help us to move towards a general theory of decision processes in trust investment. From his work, which involved building a simulation model of the trust investment process, Clarkson found that the portfolios selected were very similar to those of the manager and that a significant proportion of the manager's recorded behaviour was replicated by the model. If successful models of individual behaviour in various processes (like Clarkson's) can be built by a series of researchers then we will be able to translate theories of individual behaviour into theories of market and organisational behaviour. It is surely right that we should now work from the smallest unit - the individual firm and its complexity - and try and develop aggregate theories from sub-unit theories.

---

32. G. P. E. Clarkson, Portfolio Selection: A simulation of trust investment. Prentice-Hall. 1962.

The subject of interest in this thesis is the R & D process and bow to build operationally useful models of such processes. Some concepts from theories developed so far may be valuable in model building but in addition a detailed study of the firm, its employees, its environment, its decision processes and the relation of research and development to the objectives of the firm are extremely relevant. This observation of firm behaviour both past and present is undertaken in Parts II and III of this thesis before the model building analysis. For the moment we will try to consider which theories, a priori, seem valuable to our study. In particular we will look at the range of alternative decision theories put forward in the literature.

2.4. Concepts from the Theory of the Firm, Behavioural Theories and decision Theories Relevant to the R & D Process

Arrow[33] in his paper on the production and transmission of technical knowledge focuses his attention on the uncertainty inherent in research activity, particularly in the prediction of the outcome. In the studies described in this thesis we shall be concentrating primarily on the uncertainty aspects of research and neglect the other distinctive feature of research activity, its public goods property, with all the consequent ramifications for patent policy.

We start with a conception of economic man, a decision maker, who is confronted with choices resulting in known certain outcomes. In this highly unrealistic situation the decision maker has no decision

---

33. K. J. Arrow, "Classificatory Notes on the Production and Transmission of Technological Knowledge" AER, May 1969.

problem he merely chooses that act which confers the most desirable outcome in terms of the firm's maximisation objectives. This assumes a one to one correspondence between the decision maker and the firm. Suppose we are now to complicate this simplified model by introducing statistical uncertainty into the outcome space. There are methods available to help the decision maker in the face of uncertainty, for example, linear programming under uncertainty[34] or statistical decision[35] theory. Statistical decision theory specifically involves the use of probability in decision making situations and its development has given rise to a vast literature on subjective probability and the theory of preferences or utility theory. There is a good deal of controversy amongst statisticians about the use of subjective probability distributions and the suggestion has been made that decision makers do not maximise expected monetary value but expected utility. There are, therefore, problems concerned with the definition and measurement of subjective probability and utility which require testing and solution. Further, decision theories imply that the decision maker in the organisation is a single entity whose objectives correspond exactly with the objectives of the firm and who acts in accordance with a single maximisation objective. This is in conflict with the findings of the organisational theorists[36] who suggest a multiplicity of objectives and a satisficing criterion. In our previous discussion of the behavioural theory it became

---

34. See G. B. Dantzig, "Linear Programming Under Uncertainty", Management Science, 1955, pp. 197-206

35. See R. Schlaifer, Probability and Statistics for Business Decisions McGraw-Hill, 1959.

36. J. G. March and H. A. Simon, Organisations, Wiley, 1958.

apparent that problems of the identity of the decision maker and the relevant criterion for decision making are not understood sufficiently to make the behavioural theory effectively operational. Yet this does not mean that studies of individual microeconomic behaviour should be abandoned. In order both to understand microeconomic changes in productivity and to develop more useful micro-theories we must study behaviour of decision makers in the R & D area.

The viewpoint adopted later in this thesis is that statistical decision theory provides the most useful framework with which to analyse the inventive process. There are problems involved in the application of such methods some of which are outlined above but none of them are so destructive that allowance cannot be made for them if it proves to be necessary. However, a more thorough and detailed study of the type documented in later chapters, is necessary to solve some of the economic problems connected with the research activity. For example, the problem of allocating resources to research needs to be solved, We need to search for analytic solutions but advances in the first instance may only come through the numerical solution of particular problems, employing the techniques of the Bayesian variant of statistical decision theory. Whatever conclusion we reach it is possible that in the process some light will be thrown upon unresolved conceptual problems in statistical decision theory. In any case we will have a case study to help us evaluate the relevance of the Bayesian approach.

2.5. Summary and Conclusions

In this chapter we took as our starting point the need to investigate more thoroughly the micro-character of research activity uncovered by previous research investigators. Having outlined the distinctive micro features of research activity we evaluated the usefulness of the microeconomic theory of the firm as an analytical framework for the R & D process. It was seen that economic theory does not treat individual firm behaviour as its purpose is to predict the market behaviour of firms.

The behavioural theory was considered because it has been one of the few attempts to construct a decision making theory at the firm level. Its value is not yet clear because some conceptual problems concerning the multiplicity of objectives and the nature of the satisficing concept have not been fully resolved.

Certain concepts from economic theory and the behavioural theories will be useful for developing models to explain elements of decision making in R & D. In addition, studies of the R & D process from a decision making point of view need to be carried out at the level of the firm. These studies should be carried out in two stages:- first, the description of decision processes in R & D; second, the development of methods for the analysis of decision problems. In Parts II and III the essential first stage work in the detailed analysis of micro decision process in R & D is carried out. This is to piece together from discussion and historical evidence the formal and informal operation of the firm's decision making procedures and gather retrospective evidence on the effectiveness of R & D decisions. This is an essential prerequisite for the second stage of building models which are appropriate to the operations of the firms under study. At this second stage we consider that the Bayesian approach to decision making is the most relevant analytical method.

Part II THE QUESTIONNAIRE STUDY

Introduction

The aim of this part of the study is to provide an information base for the succeeding research on R & D. Specifically, we gain information about the processes of decision making (Chapter) and evaluate the effectiveness of past R & D decisions with information gained from the questionnaire enquiry in Part III. In Part IV we use this information as a basis for structuring models of decision problems in R & D.

The existing information base in the literature deals mainly with military R & D in the United States[1, 2, 3]. Since military R & D tends to be more technically advanced than industrial R & D, there is a clear need for some additional case study evidence on the problems of industrial R & D.

---

1. See M. Peck, R. R. Nelson, T. Marschak, Enos, Marshall and Meckling in Nelson, R.R. (ed), The Rate and Direction of Inventive Activity, Princeton, 1962.
2. T. Marschak, T. K. Glennan Jr. and R. Summers, Strategy for R & D, Berlin: Springer-Verlag, 1968.
3. M. J. Peck and F. M. Scherer, The Weapons Acquisition Process Harvard: Harvard Business School, 1962.

Chapter 3

METHODOLOGY OF QUESTIONNAIRE ENQUIRY

3.0. Introduction

In essence, the approach adopted in this work is the case study method. The rationale for the use of this method is the wealth of detailed information which can be obtained about a firm's research activity. Because the case method is used we have no statistical sampling problems since we consciously sacrifice information about a representative sample of firms in the electronics industry for more detailed knowledge of the operations of a few firms.

3.1 Questionnaire Design

The questionnaire presented in the Appendix to this chapter was designed with two requirements in mind. First, as the firms who agreed to cooperate in the study differed in their organisation structures, types of research carried out and a number of other dimensions the organisation of the questionnaire had to be sufficiently flexible to allow for such differences. Second, to provide detailed and thorough information on the development process. This second requirement includes the more difficult task of assessing the information needs and problems of the development process. We used the previous case studies and research enquiries[1,2,3] about R & D to provide the basis for the material covered in the final questionnaire.

In the final questionnaire the topics considered most relevant were general firm data, management and organisation of research and development, finance of research and development, manpower aspects of research and development and data and information on the general results of research and development.

The research method adopted, was to complement the questionnaire method with participant observation in the actual R & D operations of the firm. This researcher spent a considerable amount of time in both firms and worked there on a regular basis in order to be regarded by the employees of the firm as having the same status as them. Detailed and careful discussions were undertaken with all relevant employees in the firms studied to assure them that the research was an academic project and that any results of the work relating to specific individuals, projects etc. would not become either the property of the firm or be presented to the firm. Inevitably, discussions of this type do not really break down the barriers between the researcher and employee and the success of the observer role depends on the observer's personality and ability to fit into the organisational environment. With the two firms studied here the author spent one day a week in each over two years working the same hours as the firm's employees, occupying a desk at the factory and making sufficient personal contacts to allow the

---

1. Industrial Research in Manufacturing Industry, 1959-60, Federation of British Industries, London, 1961.
2. E. Mansfield and R. G. Brandenberg, "Allocation, Characteristics and outcome of the Firm's Research and Development Portfolio", Journal of Business, October 1966.
3. See also the military R. & D. references given in the introduction to Part II.

the work to proceed reasonably successfully. Each evening on reaching home from the firm the author tried to document in note form the facts and impressions about the workings of the R & D organisation and any comments made by employees which would tend to explain features of the organisation's environment left vague or ambiguous by answers to the questionnaire study. The participant observation process was carried on throughout the subsequent stages of the project analysis outlined in Part III and IV.

This complementary process of participant observation is similar to the social anthropologist's field study method. Since we are interested in the decision processes in R & D we must not merely accept the formal statements of objectives and mechanisms for decision making, we must also try and document the informal operation of these processes. This follows the thinking of Brown[4] in "Exploration in Management" where he postulates four organisational structure models: the theoretical, the modified theoretical, the assumed and the manifest. Brown says that we can never know the manifest organisation i.e. the one actually in operation yet it is clear that if we try to describe the informal operations of the processes under study we must approximate to the actual organisational environment.

Having outlined the research method adopted we must discuss the construction and details of the questionnaire.

---

4. W.B.D. Brown, Exploration in Management, London: Penguin Books Ltd. 1965.

The first section on general firm data is included to provide broad information on the nature of the firm's business, its methods of organisation and its financial accounts.

Section II is perhaps the most important section in the questionnaire as it covers the management and organisational aspects of research and development. Section I helps us to establish the general environment of the organisation and particularly its financial position and overall structure. In the second section the information required from the firm is made much more specific in that we concentrate upon the management of the research and development function. In order to understand the process of innovation within the firm we must first establish the type and nature of research and development work undertaken and the organisation and function of research and development within the firm. Previous research evidence[5] suggests that firms undertake different types of research work and do not always try to satisfy the same objectives by doing R & D. Further, Burns and other authorities have suggested that the organisation structures adopted for innovation management in the firm vary along a continuum ranging from no decentralisation of authority and functions within the firm to complete decentralisation. The structures adopted will in turn influence the lines of communication between the various functional areas within the firm and have associated implications for the processes of decision making within the firm.

---

5. See for example T. Burns and G. M. Stalker, The Management of Innovation, London: Tavistock Press, 1961.

The organisation structure and the objectives for undertaking R & D, be they financial or merely prestige objectives, allow us to understand the processes and mechanisms by which ideas for potential project innovations are generated. In some organisations the R & D work acceptable to the firm might be conditioned by constraints that it must fall within a given marketing policy for the firm and be capable of being undertaken by the physical resources and production facilities within the firm. In these cases ideas for projects may be generated to a large extent by customer needs as perceived by the marketing function. This in turn requires that we must find out the sources of ideas for projects and relate idea source to the subsequent effectiveness of the research project when completed.

Once we have found out the processes of project generation we must find out about the ways in which the firm and, in particular, the research and development function review the feasibility of potential projects before deciding whether or not to adopt any of them. Therefore, we must have information on the lines of communication and responsibility within the R & D department and the formal and informal procedures used in reviewing potential research projects. The information on review procedures naturally leads us to enquire about the information required by the firm and its decision makers when they have to select projects and allocate resources between them. Do the firm's management have a budget for research and development work? What factors are considered important in resource allocation decisions in research and development? These are some of the points which a questionnaire must cover in the area of the management of research and development. Yet, there is much information that can only be obtained by observation and participation in the work of the research and development function particularly the distinction between formal and informal procedures of organising jobs and making decisions. The questionnaire is thus a check list of factors which seem relevant, a priori, in highlighting the microeconomic and organisational problems in the day to day management selection and control of research projects. However, our knowledge of the microeconomic processes of innovation is deepened by the subjective observation of the researcher and this should be borne in mind in evaluating the relevance of questions in the questionnaire.

Whilst the second section is intended to be the core section of the questionnaire as it tries to bring out the nature of the innovation process the remaining three sections are designed to cover three highly important areas of the innovative process. Thus, the third section builds up our knowledge of the financial aspects of research and development and tries to gain information on the profitability of research and development work and its relation to the efficiency of the R & D department and the firm as a whole.

The manpower aspects (Section IV) of research and development are important because the availability and existence of skilled manpower resources are essential elements in the resource-mix of the individual firm. A knowledge of the type of research unit in which engineers work, the skills and publications of members of the research staff and the existence of incentive and training schemes help us to compare and contrast the efficiency of different research and development organisations.

Manpower, financial, organisational and technical aspects of the innovative process are considered to be aspects of the innovative process which require study and attention. In addition, if we wish to piece together the interactions of these factors we must try also to evaluate past research and development project results (Section V). We question whether the rate of progress was satisfactory, whether the technical problems could have been treated more efficiently, whether the control of the progress and of the effort expended on the project could have been improved and whether the organisational structure hindered the efficient operation of the project. Thus, by concentrating on some specific historical projects we hope to piece together some of the problems of the inventive process, the interactions of economic and technical factors etc., in order to understand more fully the microeconomic character of the inventive process. However, discussion of this retrospective analysis is postponed until Part III of the thesis.

3.2. Summary

The Rationale for the questionnaire approach and the research methodology adopted in this phase of the work have been discussed. In the next chapter the depth of information obtained and the processes of descision in the firms under study are described. It is important to remember that the distinctive feature of the research method is the combination of the dual advantages of questionnaire methods and participant observation.

Despite concentrating our attention on two firms in the electronics industry we believe that our case study findings in firms A and B will be reasonably representative of electronics firms. An unpublished paper by Clark[6], in which the characteristics of 30 electronics firms were studied, provides a justification for our belief in the wider applicability of the case study findings.

---

6. N. Clark, "Science and Regional Economic Development", unpublished Working Paper, University of Edinburgh, Department of Economics, 1968.

3. 3. APPENDIX TO Chapter 3

QUESTIONNAIRE ON RESEARCH AND DEVELOPMENT AT THE FIRM LEVEL

The Questionnaire given below has been constructed to give depth knowledge about R & D in the individual firm. As such it draws upon the FBI survey and a number of other government enquiries previously mentioned for detailed definitions of R & D activity.

QUESTIONNAIRE ON RESEARCH AND DEVELOPMENT

Notes and Definitions on the Questionnaire

RESEARCH AND DEVELOPMENT

1. RESEARCH is defined as original investigation towards the discovery of new scientific knowledge, either without short term objectives and/or specific products in view in which case it is termed basic research, or with particular commercial objectives where it is called applied research.

DEVELOPMENT is technical activity concerned with non-routine problems encountered in translating research findings into products and processes. This includes construction of pilot plants and design and development of prototypes.

Research and development excludes -

(a) routine analyses, routine inspection, routine production testing and routine quality control.

(b) design of manufacturing units

(c) tooling up for full-scale production after development of new plant

(d) production for sale

(e) market research

(f) pre-production of aircraft

(g) selling of an established product

(h) legal work in connection with patent applications

except where these activities are undertaken by R. & D. department for other departments and itself, in which case they should be included under technical services.

Research and Development is expressed into the seven following categories:

1. /

1. Basic Scientific Research

2. Applied Research directed towards specific new products or processes

3. Applied Research on improvements to existing products and processes

4. Development of new or existing products and processes

*5. Technical Services

*6. Informational Services

7. Any other activities. Please specify ....

....

....

*Technical Services include design of special equipment for a process.

*These include the preparation of reports, drawings, formulae, specifications, standard practice instruction, operating manuals, etc. for transmitting to production units, information obtained from other R. and D. activities.

2. ANNUAL DATA

Period covered by data should be kept comparable either on a fiscal, calendar, or accounting year basis. If this is not possible, this should be indicated where a change occurs.

Note. Firm should include information on its annual period ending year as indicated in individual questions.

LIST OF PRODUCT GROUPS

Ref. No.	Description of Product Group
	MINING AND QUARRYING PRODUCTS
1	Mining and quarrying products
	FOOD DRINK AND TOBACCO
2	Food
3	Drink
4	Tobacco
	CHEMICAL AND ALLIED PRODUCTS
5	Petroleum products (including lubricating oils prepared at refineries)
6	Paint and printing ink
7	Pharmaceutical and toilet preparations
8	Synthetic resins and plastics materials
9	Other chemicals and allied products
	METAL MANUFACTURE
10	Iron and steel
11	Light metals, copper, brass and other base metals
	ENGINEERING AND ELECTRICAL GOODS
12	Agricultural machinery (except tractors)
13	Metal-working machine tools and engineers' small tools and gauges
14	Textile machinery and accessories
15	Mining machinery
16	Boilers and boilerhouse plant
17	Industrial and marine engines
18	Mechanical handling equipment
19	Contractors' plant and quarrying machinery
20	Office machinery

Ref. No.	Description of Product Group
21	Pumps, valves, compressors, hydraulic and pneumatic power equipment
22	Industrial plant and fabricated steel work
23	Other non-electrical machinery and equipment
24	Scientific, surgical and photographic instruments, watches and clocks
25	Electrical machinery
26	Insulated wires and cables
27	Telegraph, telephone, radio and other electronic apparatus
28	Domestic electrical appliances
29	Miscellaneous electrical goods
	SHIPBUILDING AND MARINE ENGINEERING
30	Shipbuilding and ship repairing
31	Marine engineering
	VEHICLES
32	Motor vehicles (including tractors) including parts and accessories except electrical equipment
33	Motor cycles, three-wheel vehicles and pedal cycles
34	Aero engines (manufacture and repair)
35	Airframes (manufacture and repair)
36	Aircraft parts and accessories (except electrical equipment)
37	Locomotives, railway carriages, and wagons and other vehicles
	METAL GOODS NOT ELSEWHERE SPECIFIED
38	Tools and implements; cutlery; wire and wire manufactures; cases and metal boxes; jewellery; plant and precious metals; bolts, nuts, screws, rivets, etc; and other metal products not elsewhere specified
	TEXTILES
39	Man-made fibres (staple fibre and continuous filament yarn)
40	Yarn thread, cloth and piece goods of cotton, flax, silk, linen and man-made fibres

Ref. No.	Description of Product Group
41	Woollen and worsted products
42	Textile finishing
43	Other textile manufactures, including asbestos products (except asbestos cement)
	LEATHER, LEATHER GOODS AND FUR
44	Leather, undressed and dressed, and manufactures of leather and fur
	CLOTHING AND FOOTWEAR
45	Clothing
46	Footwear
	OTHER MANUFACTURES
47	Bricks, cement and miscellaneous building materials and abrasives
48	Pottery, china and glass
49	Timber and furniture etc.
50	Paper and board
51	Paper products, printing and publishing
52	Rubber and rubber products
53	Other manufacturing industries
	CONSTRUCTION
54	Building and civil engineering work of all kinds
	OTHER NON-MANUFACTURING INDUSTRIES AND SERVICES
55	Water companies
56	Wholesale and retail distribution
57	Other and general (e.g. research and development services such as those rendered by professional consultants)

List of qualifications in engineering, science and technology

For the purpose of this inquiry a "first degree or equivalent qualification in engineering, science or technology" means one of the following:-

University degree
Diploma in technology
Chartered engineer (C. Eng.)
Associateships or diplomas awarded by the following colleges or former colleges. (Some are now universities.):-

	Abbreviations of awards
The Camborne School of Mines	A. C. S. M. or Dip. C. S. M.
The City and Guilds of London Institute	A. C. G. I.
The Cranfield College of Aeronautics (Diploma)	Dip. of
The Heriot Watt College	A. H. W. C.
The Manchester College of Science and Technology	A. M. C. S. T.
The Robert Gordon's Technical College, Aberdeen	
The Royal College of Science (London)	A. R. C. S.
The Royal College of Science (Ireland)	
The School of Mines	A. R. S. M.
The Royal College of Science and Technology, Glasgow	
The Imperial College of Science and Technology	A. R. C. S., A. R. S. M., A. C. G. I.

Graduate or corporate membership of:-

The Royal Aeronautical Society
The Institute of Biology
The Institution of Chemical Engineers
The Royal Institute of Chemistry
The Institution of Civil Engineers
The Institution of Electrical Engineers
The Institution of Electronic and Radio Engineers
The Institution of Gas Engineers
The Institute of Marine Engineers
The Institution of Mechanical Engineers
The Institution of Metallurgists
The Institution of Mining Engineers

The Institution of Mining and Metallurgy
The Institution of Municipal Engineers
The Royal Institution of Naval Architects
The Institute of Physics and Physical Society
The Plastics Institute
The Institution of Production Engineers
The Institution of the Rubber Industry
The Institution of Structural Engineers
The Textile Institute.

Technicians and other technical supporting staff

These occupy a position between that of the Q.S.E. on the one hand and the skilled foreman or craftsman on the other. Their education and specialised skills enable them to exercise technical judgment. By this is meant an understanding by reference to general principles, of the reasons for and the purposes of their work, rather than a reliance solely on established practices or accumulated skills. They may possess qualifications such as Higher or Ordinary National Diploma or certificate, or the City and Guilds or similar nationally recognised awards. Some may possess a degree in science, engineering or technology. If a person does not possess a formal qualification this does not mean he is not a technician. In identifying technicians and other technical supporting staff it is essential to consider the job being done rather than the qualifications held. Persons under training as technicians or other technical supporting staff should be included.

Range of functions of technicians and other technical supporting staff

They are normally encountered among workers in the following fields:

(a) The detailed design and development, or the manufacture, erection or commissioning of equipment and structures; drawing estimating, inspecting and testing equipment: use of measuring instruments: operating, maintaining and repairing machinery: activities connected with R. & D., testing of materials and components; technical advice to customers; servicing equipment; data processing; work study.

(b) assisting qualified scientists in physical measurements; collection and evaluation of experimental observations; devising and setting up of experimental apparatus; preparation of chemicals or biological cultures or similar preparations in other fields; photographic work; taking and routine testing of product samples, chemical analysis, etc.

Main Job Titles

Computer operators and programmers, designs assistants, draughtsmen, other design and drawing office staff, laboratory technicians, plant and site supervisors, installers, etc., and service engineers, production planners, research assistants, technical sales and service staff, testers, calibrators, inspectors, analysers.

Other job titles:

Cotton spinning and weaving:	Automatic loom overlooker Carder or spinning overlooker Fabrics designer Laboratory Assistant
Food Processing	Domestic Science Worker Food Process Technician Industrial Photographer Quality Inspector Skilled estimator Skilled experimental chef
Construction:	Buyer Contract Manager Estimator Quantity Surveyor Site Manager
Engineering:	Junior stressman Process Foreman Technical Writer Work Study Specialist
Other Industries:	Carpet Planners Hosiery Mechanics Operational Research Assistants Soil Mechanics technician Safety Officers

(Note: There are obviously many more job titles describing the function of technicians and other T.S.S. than given here. The lists are not to be taken as exhaustive and are merely illustrative.)

ENGINEERING, TECHNOLOGICAL and SCIENTIFIC SUBJECTS

CHEMICAL ENGINEERING

Chemical Engineering
Gas Engineering

CIVIL AND STRUCTURAL ENGINEERING

Civil Engineering
Structural Engineering
Municipal Engineering

ELECTRICAL ENGINEERING

Electrical Engineering
Computer Science
Control Engineering

MECHANICAL ENGINEERING

Aeronautical Engineering
Agricultural Engineering
Automobile Engineering
Marine Engineering
Mechanical Engineering
Naval Architecture

METALLURGY

MINING ENGINEERING

Mining Engineering
Minerals Engineering

OTHER AND COMBINED ENGINEERING

Combined Engineering
Nuclear Engineering
Production Engineering

TECHNOLOGY

Building Technology
Food Technology
Fuel Technology
Glass Technology
Material Technology
Printing Technology
Textile Technology

AGRICULTURE

Agriculture
Agricultural economics
Forestry
Veterinary Science

BIOLOGY

Biology
Botany
Agricultural biology
Anatomy

CHEMISTRY

Agricultural chemistry
Applied chemistry
Biochemistry
Pharmacology

GEOLOGY

MATHEMATICS

Mathematics
Mathematical Statistics
Numerical Analysis

PHYSICS

Applied Physics
Physics

OTHER AND COMBINED SCIENCE

Cybernetics
Ergonomics
Meteorology
Oceanography
Mathematics/Physics
Mathematics/Education
General Science
Combined Sciences

, III

QUESTIONNAIRE ON RESEARCH AND DEVELOPMENT

Name and
Address
of Firm ....

PART I - GENERAL DATA ON FIRM

A. Status of Firm

1. Are you owned or controlled by another company? Yes/No

2. If owned by another company, when were you acquired?

3. (a) If you are a subsidiary or affiliate of a company overseas, please name company, and country.

   (b) If a subsidiary or affiliate of a company whose headquarters are in the U. K., please name company, and country.

4. Do you have your own board of directors? Yes/No

5. How much control does your management have over decisions such as financial, employment? Please expand.

6. If the answer to Question 1 is Yes, what is the composition of your board of directors between your own and that of the controlling firm?

---

7. Does your board of directors have complete control over financial, employment, investment and management decisions in the firm? Please expand.

---

8. Do you publish your own accounts separately? We should like a copy of the accounts, if possible. (Past five years) Yes/No

---

9. Have there been any changes in your method of accounts over past five years (or ten)? If so, please explain.

---

10. What is your financial year? See Note 2 in Definitions (i. e. on what basis).

B. Firm Data

	1968	1967	1966	1965	1964
1. Pre-tax profits £					
2. Net Sales £					
3. Total employment in all activities					
4. Total wage-bill of all employees, including Nat. Ins. and Pension Contributions £					
5. Capital Expenditure (excluding depreciation): a) Land, Buildings £ b) Plant, equipment, vehicles £					
6. Value of Stocks: a) Raw Materials b) Finished products c) Work in progress					

Note: Please explain firm's method of depreciation and any changes in past five years.

7./

114

7. a) Into which Product Group or Groups do your products fall? (See key to Product Groups in Definitions.)

b)	Product	Price	Output
Give prices and physical output in most recent year of the 10 principal products into which the output falls.			

C. <u>Firm Operations</u>

1. Give addresses where the following activities are carried out:

a) Production

b) Research and Development

c) Sales

d) Adminstration

PART II. MANAGEMENT AND ORGANISATION OF R. & D.

1. (a) Do you accept the following seven categories of research and development as being sensible for your organisation?

    (1) Basic scientific research.
    (2) Applied research directed towards specific new products and processes.
    (3) Applied research on improvements to existing products and processes.
    (4) Development of new or existing products and processes.
    (5) Technical services.
    (6) Informational services.
    (7) Any other activities: please specify.

    (b) Could you talk about the work undertaken in your organisation in these categories?

    (c) Could you make an estimate of the number of current projects in each category?

    (d) Could you ~~will~~ fill in the following table which seeks to gain information about the percentage distribution of research projects by category of research for the period 1964-1968?

Percentage of Research Projects by Category of Research, 1964-1968

(Here 1968 - means year ending 1968)

	1968	1967	1966	1965	1964
Basic Scientific Research					
Applied New Product Research					
Applied existing Product Research					
Development					
Technical services					
Informational services					
Any other					

2. (a)

(i) To what extent do other departments in the firm undertake their own R. & D. activities? (Answer with reference to your current year.)

(ii) Has the position been changing over the last five years?

(b)

(i) Can you estimate the percentage of R. & D. activity in the firm in the current year that is undertaken by the R. & D. department?

(ii) Is it possible to make estimates of this percentage for the last five years?

The following table may make it easier to answer this question:

Percentage of R. & D. Activity undertaken by the R. & D. Department in the following years

	Current year	1968	1967	1966	1965	1964
Percentage						

(c) Do other departments put up ideas to the R. & D. Department for scientific evaluation?

3./

3. What are the main function(s) of the R. & D. department in your organisation?

   e.g. (i) as a service department

   (ii) as a major source of new ideas and research

4. What do you think that the R. & D. organisation can most usefully do in order to maintain the profitability of the firm?

5. Is the R. & D. department on a different site from other departments in the firm?

6. To what extent does the R. & D. department have autonomy in its operation?

   e.g. (i) in FINANCIAL matters: can you spend money allocated to your department in whatever way you think fit?

   (ii) in ORGANISATIONAL matters: can you hire employees freely?

7. (a) To whom are you responsible in the firm and to whom do you report on the performance of your various activities?

   (b) Are there any other poeple to whom you must answer?

8. What are the lines of responsibility within the R. & D. department?

   e.g. do you employ project leaders superintending project teams or is your organisation different from this pattern?

9. (a) What is the relation between your department and other departments in the firm, e.g. finance, production, marketing, sales, the central board?

(b) With which departments do you communicate most?

(c) What proportion of specific requests are made of the R. & D. department by these other departments?

From which departments do these requests come?

(d) Do ideas for future research topics, other than these specific requests, come much from outside the R. & D. function?

If YES: What proportion come from outside and from which departments?

10. (a) If requests are made by other departments, who from the other department contacts the R. & D. organisation? (For example, does the person who thinks up the idea contact the R. & D. department directly or does he communicate with his own functional management first?)

(b) Do these requests from other departments tend to be for basic or applied research?

(c)/

(c) Is it possible for the team to look at certain current requests from other departments and see both how they are treated and what happens to them eventually?

(d) Are there records available of requests made by other departments to the R. & D. department over the last five years?

If YES, would you fill in following table.

Percentage of Requests from Other Departments by Type of Activity

	1968	1967	1966	1965	1964
Basic Research					
Applied new product					
Applied existing product					
Development					
Technical Services					
Informational Services					
Other (specify)					

11./

11. (a) Is each idea that is received by the R. & D. department from other departments scrutinised by the R. & D. manager first?

Yes/No

If YES: After the manager has looked at it does he then pass it on to one of his staff for evaluation before a preliminary decision on its viability is made? If not, what is the procedure that is then followed?

If NO: If there any procedure in practice by which these ideas are reviewed?

(b) Is it possible for the team to look at some ideas that have recently been put forward to the R. & D. department by other departments to see how they are treated initially and also what the subsequent stages in the evaluation procedure are?

(c) If records of ideas put to the R. & D. department by other departments (over the past five years) are available, would you please complete the following table?

Percentage of Ideas from Other Departments by Type of Activity

	1968	1967	1966	1965	1964
Basic research					
Applied new product					
Applied existing product					
Development					
Technical services					
Informational services					
Other (specify)					

12. (a) Ideas are generated also within the R. & D. department? Can these ideas be categorised by the seven types of R. & D. activity for both the current year and the past five years?

Percentage of Ideas Generated within R. & D. Department by Type of Activity

	1968	1967	1966	1965	1964
Basic Research					
Applied new product					
Applied existing product					
Development					
Technical services					
Informational services					
Other (specify)					

(b) What is the procedure for evaluating these ideas within the R. & D. department?

NOTE: It is perhaps worthwhile here to make some comments about what we are trying to find out at this stage of the questionnaire. We are trying to find out the lines of communication within the R. & D. department and between the R. & D. department and other departments of the firm as regards R. & D. activity. We are not trying to tackle the problem of evaluation here - this is treated later on - but rather to get an understanding of where ideas and requests come from and by what process they emerge as projects to be evaluated further later on. We must also emphasise that an idea may have a different level of formality in the process than a request has. It is obviously useful for us to know that ideas and requests are treated in different ways according to their different levels of formality.

13. (a) At what stage are these internally generated ideas merged with the externally generated ideas and requests? Are internally generated ideas treated any differently from externally generated ideas and requests? e.g. are greater priorities attached to internally generated ideas?

(b) Is it possible to get data for the past year (and, if possible, the last five years) on the proportion of ideas that eventually get accepted whether those ideas be internal to the R. & D. department or external to it?

Perhaps a table would help you in your answer.

Proportion of Ideas that eventually get Accepted

Source of ideas R. & D. Department					Source of ideas Other Departments				
1968	1967	1966	1965	1964	1968	1967	1966	1965	1964

14. /

14. Do you feel that after a preliminary evaluation of a request or any idea, such as is made at this stage of the decision process, you could make a judgement about the probability of its technical or commercial success?

If YES: On what grounds would you justify your probability estimate?

If NO: (a) What further information do you need?

(b) What further things would you like to see done?

NOTE: We are now asking a question about the total budget because it is a relevant factor in the evaluation of, and allocation of resources, to projects.

15. (a) Does the firm have a total R. & D. budget?

(b) Is this budget defined in terms of:

(i) a specific cash sum?

(ii) a certain number of projects?

(iii) other (please specify)?

(c) As a matter of policy, do you restrict your investment programme to those acceptable proposals which can be financed out of internally generated funds?

16. Is the research and development director or manager given full responsibility to administer his budget resources in whatever way he thinks fit?

If NO: with whom does the final authority lie on the administration and allocation of the budget?

17. (a) What information do you collect in the R. & D. department about production licensing agreements and patent rights held elsewhere but which might be useful to the firm's operative?

(b) What information do you collect about R. & D. going on

either (i) in firms in the same industry?

or (ii) in firms in other industries?

or (iii) any other places (please specify)?

(c) What sort of analyses are made of business and market conditions by the firm?

Are these analyses fed to the R. & D. department?

(d) Are profits and sales figures fed to the R. & D. department?

(e) Do you think that information about external and internal conditions (as outlined above) needs to be collected by the R. & D. department? What reasons would you give for assembling such information?

18. We have tried to see how informal ideas and requests are made to the R. & D. department and how they are formalised after a preliminary evaluation. Now, what happens to these formalised research possibilities?

(i)/

(i) (a) Are they considered individually or does the managerial organisation decide to look at them after a quantity has amassed?

(b) If done in batches, how many batches per year do you deal with?

(ii) Who decides that the process of consideration is done in the way described in (i)?

(iii) Why is the process done in this way?

(iv) How often do you submit R. & D. estimates up to the board?

19. Please elaborate on the method or methods by which your firm measures the relative investment worth or economic desirability of proposals submitted for inclusion in your R. & D. budget.

(a) Simple rate of return on each investment is estimated.

(b) Discounted cash flow (DCF) method is used.

(c) Net present value calculation made.

(d) MAPI formula employed.

(e) Payback period calculated.

(f) Subjective judgement applied.

(g) Other measures.

20. Against what standard(s) do you compare the relative worths (as provided by the measure(s) denoted above) of the various proposals under consideration to determine which to accept and which to reject.

(a) An arbitrary "cut-off". Please note the specific value which serves as your standard (e.g. you may consider as acceptable all proposals with an indicated payback of less than three years or a rate of return not less than 10%).

(b) An historical average return on the book value of the company or division.

(c) A weighted cost of capital.

(d) Other.

21. *

	Measures (a)	(b)	(c)	(d)	(e)	(f)	(g)	Standards (a)	(b)	(c)	(d)
(a) Convenience											
(b) Proven on the basis of past experience											
(c) Cost											
(d) Timeliness											
(e) Suitability											
(f) Not preferred - a change is being contemplated											
(g) Other											

*/

127

*For which of the reasons shown overleaf does your firm prefer the measure(s) and standard(s) indicated in your previous responses?

(b) If you wish to elaborate on any of the reasons please do so now.

22. How have your measure(s) and standard(s) changed over the last five years?

23. If you are contemplating a change in the immediate future in either your measure(s) or investment worth or standard(s) of comparison, what measure(s) or standard(s) are being considered, and why?

24. (a) As a matter of policy, are projects given a definite expectation of life when they are first approved?

(b) How is this length of time or period of life determined?

(c) Also, at what resource level (or strength) do you decide to back projects? (e.g. if you put limitless resources into some projects they would have a higher probability of showing tangible results eventually).

25. (a) How often are projects:

(i) evaluated

(ii) reviewed

(b) Do existing projects come up for renewal each year or at the end of their lifetime?

(c)/

(c) How do you review and appraise the performance of projects in operation?

(d) How often are budgets allocated to particular projects?

26. How do you incorporate the element of risk amd uncertainty into your evaluations?

(a) By adjusting investment worth figures to reflect the different levels of risk associated with individual proposals?

(b) By applying different "cut-off" rates to projects of different degrees of uncertainty?

(c) No attempt is made to incorporate risk and uncertainty into our evaluations.

(d) Other method(s) used.

27. (a) What budgetary control techniques are used to control the spending of the R. & D. budget?

(b) Is a separate account kept for each project?

If YES: are budgetary control techniques used to control spending on that project?

28. If the resources given to a particular project were exhausted, would additional resources for that project be available from the central pool?

PART III. THE FINANCE OF R. & D.

NOTE: Earlier in Part II we looked at the question of an overall budget set aside for R. & D. work in the organisation.

1. Is the total budget planned in advance?

If YES:

(a) How is the budgeted figure calculated?
e.g. Do you decide to spend so much on R. & D. or do you just decide to support a certain number of projects?

(b) What factors are considered in your calculation?

(c) To what extent do you take account of:

(i) production leasing agreements with other firms

(ii) research carried out by other firms in the firm's industry

(iii) research carried out by other industries (please name)

(iv) general business conditions or forecasts

(v) profits or sales results

(vi) government actions, e.g. credit squeeze

Then, can you give us some examples of how you take account of these topics listed above?

2. (a) Are figures available of planned or budgeted spending on R. & D. for each year for the past five years?

(b) In all cases what was the actual spending? Please enter figures below.

PLANNED BUDGET					ACTUAL BUDGET				
1968	1967	1966	1965	1964	1968	1967	1966	1965	1964

3. If there is no definite planned figure available for R. & D., what was the actual spending on R. & D. (Again for the last five years.)

ACTUAL BUDGET				
1968	1967	1966	1965	1964

4. (a) Is it possible for the figures for total current expenditure on R. & D. to be broken down by type of R. & D? (As in the following table.)

	No. of projects for year in question	Staff	Material Costs	Capital goods, e.g. machinery breakdown of new/old machinery	Overheads Plant and Buildings
Basic Research					
Applied New Product					
Applied Existing Product					
Development					
Technical Services					
Informational Services					
Any other activities (specify)					

(b) Can this breakdown also be obtained for each of the previous five years?

5. What is the smallest unit costed separately? (e.g. does each individual project have its own account?)

6. What is your accounting year?

7./

7. What was the cost breakdown in the R. & D. department, for each of the last five years and the current year, between labour costs and material costs.

NOTE: This is not the same question exactly as (4) because we are seeking the aggregate breakdown here, i. e. we are not trying to distinguish types of R. & D. activity.

Cost Breakdown for R. & D. Department

	Current Year	1968	1967	1966	1965	1964
Labour Costs						
Material Costs						

8. In question 4 we have as one of our cost components:-

OVERHEAD COSTS

(a) What does this overhead cost component consist of?

(b) How far is an attempt made to assign overhead costs, where these are used by all activities of the firm, to the R. & D. department?

9. (a) What does external expenditure on R. & D. consist of?

Could you detail your expenditure in each of the following categories for the current year (please add further categories that appear to be necessary for your firm).

(i)/

133

(i) Payments for R. & D. work by subsidising to parent firms

(ii) Payments for R. & D. work to either government or private research associations or both (please distinguish between regular subscriptions and specific work).

(iii) Payments for R. & D. work to private consultants

(iv) Payments for R. & D. work to universities

(v) Payments for royalties

(vi) Payments for licensing agreements

(vii) Payments for patent infringements under patent fields

(viii) Any other (please specify)

How many pieces of work are given to outside bodies? Can these figures be broken down?

Could you also give this information for each of the previous five years?

(b) Could these payments also be broken down by type of R. & D. activity as illustrated in the following table, for the current year and each of the previous five years?

134

Payment Breakdown for Current Year

Question 9(a)

R. & D. activity	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
Basic research								
Applied new product								
Applied existing product								
Development								
Technical services								
Informational services								
Any other								

(c) Can you also give some indication of the number of production leasing agreements entered into by the firm?

	1968	1967	1966	1965	1964
Number of Production Licensing Agreements entered into by firm					

10./

10. (a) What does external income from R. & D. work consist of? Could you detail the income in each of the following categories for the current year (please add any further categories you think necessary).

(i) From R. & D. work sold by the organisation to outside bodies.

(ii) From licensing agreements.

(iii) From payments to the R. & D. department by other subsidiaries of the firm.

(iv) From royalties.

(v) From patent infringement under patent fields.

(vi) Any other (please specify).

Could you also give this information for each of the previous five years?

(b) Could these sources of income be identified by type of R. & D. activity, as illustrated in the following table, for the current year and each of the previous five years?

Income Breakdown for Current Year
Question 10(a)

R. & D. Activity	(i)	(ii)	(iii)	(iv)	(v)	(vi)
Basic research						
Applied new product						
Applied existing product						
Development						
Technical services						
Informational services						
Any other						

(c) Can you also give some indication of the number of production leasing agreements entered into by other firms with your firm?

	1968	1967	1966	1965	1964
Numbers of agreements					

(d) Can you also give a list of patents taken out by the firm in:

	1968	1967	1966	1965	1964
List of Patents					

PART IV. MANPOWER DATA FOR DEPT.

A.

		1969	1968	1967	1966	1965	196
1.	Total number of qualified scientists and engineers (include full-time equivalent of those working part-time in R. & D. and in rest of dept.)						
2.	Total number of technically-qualified supporting staff employed in R. & D. teams, and other staff in full-time equivalent in firm						

3. Please give the following information (on attached sheet) on each individual Q. S. E. in your employment. Identify each Q. S. E. by number only.

4. Project Manpower	Type of R. & D.	Number of Q. S. E. in full-time equivalent on it	Number of techni cal supporting staff in full-tim equivalent
Project 1			
Project 2			
Project 3			
etc.			

139

se of Manpower

. Do you have a library for use by R. & D. scientists? Yes/No

. Do you employ a full-time information officer? Yes/No

. Do you have contacts with outside sources of information such as libraries, etc. in parent firm or others, research associations, universities and government research stations? If so, name these.

. How many of your R. & D. staff have been to the following (with your knowledge and financial help, if required) in the past year?

Scientific Conferences ....

Professional Meetings ....

University Courses ....

How much was spent by you on above, if known? £

1968	1967	1966	1965	1964

). How many of your R. & D. staff are known to be working for higher degree or engaged in studies connected with present occupation during firm's time?

0. How many of your R. & D. staff have visited other firms, such as parent firm, subsidiaries, private research firms or others on R. & D. business in past year?

1. Do you have an established number

(a) of posts for Q. S. E. Yes/No

(b) if yes to (a):

(i) What is the size of your current establishment?

(ii) How is this establishment determined?

Vacancies (Note: The following questions refer to the most recent complete year for which the firm has data.)

	1968	1967	1966	1965	1964
2. (a) Number of Q. S. E. recruited in					
(b) Number of Q. S. E. who resigned in					

3. Number of unfilled vacancies in current year under the following categories:

(a) because of resignation

(b) creation of new posts

(c) unsuccessfully filled

4. (a) How far ahead do you estimate your requirements for Q. S. E. ?

(b) If longer than one year, why is this

141

15. What proportion of vacancies for Q.S.E. were filled by:

	%
Advertising	______
Informal contacts	______
University recruitment	______
Other	______

in the past year

---

16. (a) If a post cannot be filled, would a scientist with a lower level of training than first insisted upon be acceptable? Yes/No

(b) If answer to (a) is yes,

(i) How often does this happen ______

(ii) For what sort of posts would this be acceptable? ....

(c) If answer to (a) is no, then how long will the firm wait before re-offering the post at increased salary or re-advertising? ______

---

17. Before advertising, will attempts be made to fill a post from within? Yes/No

---

18. (a) For how long are Q.S.E. usually appointed? ______

(b) What are the terms of notice on either side? ....

---

9. Do you keep salary scales for Q.S.E. Yes/No

If so, please expand ....

....

---

10. What weight do you give to age and period of employment in fixing salaries. Please expand. ....

....

Number	
Qualifications	
Age	
Present annual salary	
Period of employment with firm	
Occupation and post before joining firm	
Present position	
Changes in position in period of employment	
*Nature of work at present	
**If working in R. & D. under which type	
Subject working in at present	

Notes: / In terms of degrees, post-graduate degrees, diplomas, etc., and subject studied (see pages 6, 7, 8, 9 of definitions).
* If subject is working in more than one capacity, please indicate main one, and note others.
** If Q.S.E. is engaged in more than one R. and D. activity, please indicate main one, and note others.

ART V. GENERAL RESULTS OF RESEARCH AND DEVELOPMENT

. Project Performance

1. We would like to do a cohort analysis of a selected number of projects through the past five years in order to evaluate the performance of projects retrospectively, both from the point of view of technical success and commercial success. Please refer to the separate tables attached.

B. Patents and Licensing Agreements

2. Does the existence of patent rights held by other firms, in any way deter you from certain fields? If so, please give examples. ....

....

....

....

3. To what extent are licensing agreements for R. & D. bought from parent company? ....

....

4. Give the main influences that lay behind all licensing agreements bought by you. ....

....

C. Use of Outside Research Bodies

5. How many problems have you given to outside bodies over past 2 years?

   (i) Research Associations ....

   (ii) Government Research Stations ....

   (iii)/

145

5. (contd.)

(iii) Universities ....

(iv) Parent Company ....

(v) Private Research Firms * ....

---

6. Give the main reasons that make firm use Research Associations. ....

....

---

7. (a) Have you been satisfied with the outcome of sponsored research given to:

Research Associations ....

Universities ....

Parent Company ....

Government Research Stations ....

(b) Can the firm estimate the success-rate of such research? ....

....

---

8. Number of visits made by your R. & D. staff to:

Research Association ....

Universities ....

Parent Company ....

Private Research Firms ....

Government Research Stations ....

in past 2 years.

146

9. Number of visits to you in past 2 years made by:

Research Associations ....

Universities ....

Parent Company ....

Private Research Firms ....

Government Research Stations ....

---

10. What practical use have you made of results of Research Associations, other than specific problems referred to them? ....

....

....

---

11. How had these results come to your knowledge? ....

....

---

12. Does distance between Research Associations, and other outside bodies, and you handicap your use of them? ....

....

---

13. What other factors deterred you from using Research Associations, and other outside bodies, more? ....

....

....

---

14. Would the firm have used the services of Private Research firms to a greater extent if more of these services had been available? ....

....

....

---

15. Name other forms of co-operation in R. & D. between you and your parent company, e.g. exchange of scientists.

....

....

---

*Private research firms do sponsored research for other firms as a profit-making activity.

148

ROJECT I

'YPE OF R. & D. ACTIVITY .... When Initiated ....
–see definition in Part 2)

	Prior to initiation	1st year	2nd year	3rd year	4th year	5th year	6th yea
l rate of							
l chance of							
l date for on							
-l No. of Q.S.E.							
-l expenditure							
xpenditure							
).S.E. on project							
definitely reviewed, or terminated during l of period							
nated, give reason							
technically successful ++ f period (give date)							
ve expected period before cial success +++							
ive reason							
ercially successful, f resulting innovation. +							
escription*							

149.

	Prior to initiation	1st year	2nd year	3rd year	4th year	5th year	6th yea
nvestment necessary ment. **							
ital stock required or d stock							
s Price of product							
ce of product							
s output of product							
output after innovation							
in profits as result of on							
mmercial outcome materially from that d, please give details							

* e.g. cost reducing, quality improvement; new and improved product.

** If also included in R. & D. expenditure, please note this.

/ Where the answers to this question are estimates rather than actual figures, please mark thus - '/'.

// Technical success/failure involves the project being judged technically feasible/not feasible.

/// Commercial success involves, e.g. producing a marketable product.

In the case where research continues after an innovation has become a success commercially, we would like you to follow this through where for example research continues to find potential applications for a new product.

PART II

Chapter 4

AN ANALYSIS OF DECISION PROCESSES IN R & D

4.0 Introduction

The aim of this chapter is to discuss the nature of research and development activity at the level of the firm. We consider the problems faced in research and development work and the decisions made by the decision maker in the firm. We seek to determine the nature of the methods used in the processes of decision in R & D but leave an analysis of the effectiveness of historical R & D work in the firm with its associated implications for decision making to Part III of this thesis. Our purpose is to understand the formal and informal decision processes in R & D in the firm and to incorporate evidence from the questionnaire study to further this purpose. However, there are sections and questions in our questionnaire which we shall not consider because they do not help our understanding of decision processes.

In order to make our subsequent analysis meaningful we should present a few introductory remarks about the firms A and B who cooperated in our case study research. Both firms manufacture electronic instrumentation and have premises in the central belt of Scotland.

Firm A is the British subsidiary of an international electronics firm. Its policy is determined wholly within Britain and it is autonomous in financial and other managerial matters. Its finance for growth is generated out of sales volume though in extremely exceptional circumstances finance can be raised from the parent company. Present annual money sales volume is in the range of £3-10 million and for R & D expenditures are in the range of £0.25 - 1.5 million. R & D as a proportion of sales volume has been increasing over the last ten years and there is no evidence to suggest that R & D expenditure is some constant proportion of money sales volume.

Firm B is a private British electronics firm and is somewhat smaller in terms of sales volume and R & D expenditures. Sales volume is in the range of £1 - 3 million and R & D expenditures are in the range of £0.025 - 0.15 million. Sales volume has increased over the last ten years though R & D expenditures have risen less than in proportion to the rise in sales volume. High risk projects involving largish sums of money are not usually undertaken without external backing.

In firm A the ratio of overhead costs to materials costs for the R & D department is approximately 1:1. Unfortunately for firm B accounting data could not be broken down accurately to give a similar ratio for the R & D department in B. This is mainly because of difficulty in defining the R & D department in B. If, however, we regard the firm as the R & D department in B the ratio of overhead costs to materials costs is approximately 1:1 also.

4.1. The Notion of a Decision Process

Theories of decision making are based upon the study of the ways in which people make (and ought to make) decisions. Many theories exist and these vary from the statistical theories of decision to the organisational theories of decision. Yet whilst theories are useful their worth improves if, and only if, we constantly improve our understanding of the nature of the problems in the decision process under study.

We have as our area of interest the R & D process at the level of the individual firm. The research and development process concerns itself with the search for possible research opportunities, the evaluation of these opportunities in a formal or informal manner, the comparison between alternative research opportunities and the selection of the set of opportunities to be undertaken as the research work by the firm. This process continues through time and in addition to constant evaluation of new projects the progress of existing research work is reviewed and compared with new research opportunities for the firm.

The research and development process thus has a number of stages. What, however, is the nature of the decision to undertake R & D? Is it purely an investment decision undertaken with the motive of future profit or are technical criteria important in the decision? What are the particular characteristics of the innovative process? These are some of the more important points in our subsequent study.

We have to be careful, nevertheless, of several pitfalls in our analysis of decision processes in R & D. First, we must be aware of the difference between describing legitimate structures within which research and development decision making may be carried out and the nature of the decision process itself. In any firm there is some procedure for decision making in R & D i.e. a decision making structure but merely describing this procedure is not sufficient for a deep analysis of the decision process in R & D. We are merely describing structures for decision peculiar to the individual firm rather than the nature and characteristics of the decision process itself. The process of making a decision is complex and is related to the nature of the particular decision structure. It is basically a process of thinking and evaluation by a decision maker and is performed in relation to thelogical apparatus personal to the decision maker. The decision maker acts according to his information and knowledge of the environment, i.e. the R & D process, and the particular decision problem and is conditions by the goals or objectives which he desires to attain. The manner in which the process of decision is carried out is a function of the decision maker's subjective weighting of the relative importance of information, hunch and personal and corporate goals.

Second, in considering structures which are helpful for decision making, we must draw the distinction between the formal decision making structure or method and the informal operation of that method. A method for evaluating the worth of some R & D project may be formally put forward by the firm's management but the way in which it is used in practice may differ radically from management's initial conception.

Third, given that we can identify the decision maker in the firm, how can the processes by which he makes decisions be evaluated? It is quite clearly not sufficient to adopt the approach of asking him what decision he is making on a regular or periodic basis because of the different goals and personality structures of the decision maker. When we are trying to conceptualise an instinctive process such as the process of making a decision we must observe the decision maker's personal behaviour and his role in relation to other individuals in the firm. The effectiveness of the decision maker in relation to the sub-organisation which he controls has implications for the eventual quality of the R & D work performed by those under his control.

Fourth, this leads us naturally to an analysis of the influence which the particular organisation structure has on the decisions taken by the decision maker. The decision maker's objectives may diverge widely from corporate objectives if reward structures which recognize the worth of the decision maker are not present in the firm. He will be encouraged to set his targets in accordance with the firm's if his reward improves by doing so. Further, the existence of a well-defined information and data processing system within the organisation has an influence on decision because it will tend to alleviate the need for the decision maker to act as an information processor on information generated routinely within the firm and should thus increase his efficiency.

Therefore, we have a model of a decision maker acting in an uncertain environment, namely, research and development. The actual decision d, is a function of the research and development problem, the available information on that problem, the environment of the firm, and the objectives and goals of the firm and decision maker (which are in general dissimilar particularly if the decision maker and firm are not the same entity.)

Mathematically, $d = f(\text{R \& D Problem}, \text{Information}, \text{The Firm}, \text{Objectives \& Goals of Decision Maker})$

We have shown that the environment of the firm is important and in particular, that the presence of structures or procedures for decision making within firms is a means of developing a process of communication between individuals involved in a particular decision problem and a structured "vocabulary", quantitative or qualitative, with which they can communicate on a common basis. We must turn now to a brief consideration of information necessary for decision making.

4.2. Information for Decision Making

The decision maker must have information on the factors affecting his decision. In our analysis of the processes of decision we must, therefore, consider the information needs of the decision maker. In relation to research and development there seem to be three sets of factors which are worthy of detailed consideration. They are economic, technical and organisational factors. The decision maker needs information on the costs and benefits in economic terms of undertaking particular research projects. This information must be mixed with an evaluation of the technical feasibility of a project in relation to the firm's mix of physical resources and technical skill. Such an evaluation may be presented as an information flow from a project engineer to the decision maker responsible for research and development. Economic and technical information must be merged with information available from the organisation as a whole on budgets for research and development, plans for company growth and objectives and targets which research work must satisfy. A priori it is reasonable to suppose that the decision maker with better information will on average make better decisions and that, therefore, a firm with a well designed information system will be more efficient in its decision making. However, we should note the distinction between a good decision and a good outcome in this context. A good decision is a logical decision based on the uncertainties that are present in a given situation but it does not necessarily lead to a good outcome.

In the analysis that follows we consider the decision process itself in terms of its rationality and leave the measurement of the efficiency of past R & D results, which doesn't bear on the processes of decision, until Part III of the Thesis.

4. 3. An Evaluation of the Decision Processes in Firms A and B in the Electronics Industry.

We know that the decision maker in research and development acts in an uncertain environment and we require to analyse the reasons why particular strategies are adopted. The firms A and B have been chosen because they have widely divergent structures within which decision problems can be analysed. These structures are merely legitimate methods of viewing a decision problem. Since the words formal and informal have been used in another sense previously we shall distinguish between rigid and loose structures which help the evaluation of decision problems in research and development. A rigid structure is one in which facts and assumptions about a particular R & D problem are formalised and related together in some particular analytical form. This analytic form is often an explicit independent variable considered by the decision maker as a part of his information base in coming to a final decision. A loose structure is one in which at best only very rough numerical and factual analyses are carried out. The decision maker in such an environment looks at a given problem as a whole and comes to a decision on the basis of hunch, judgement and experience.

In our analysis of decision processes in A and B we will constantly keep in mind the functional form relating the decision to information and knowledge, the nature of the organisation and the goals of the decision maker and firm as the model for the analysis. Thus, it is legitimate to discuss the influence of the independent variables related to the decision before finally analysing how the decision maker (or group of decision makers) proceeded to the eventual decision in a particular case.

Firm A's main objective for undertaking research and development work is stated by corporate management as being the need to provide the base on which the long term growth of the company can be developed. In operational terms this means that research and development work has to achieve a level of profitability in order to maintain the future growth of the firm out of internally generated funds. It is not surprising, therefore, that the research and development work in the firm is applied in nature and oriented towards the development of new and existing products. Research and development is organised on a departmental basis with a manager appointed to direct its operations. The links between the managing director and the heads of the various sub-departments such as R & D are close and weekly management meetings at which the R & D manager and sub-managers are present are regularly held. There has always been a special relationship between the R & D manager and the managing director because of the strategic importance of R & D work to the firm. Their philosophy is basically that without good R & D they might as well go out of business. This philosophy is an offensive one, R & D is there to develop new areas of technical competence in advance of the competitor.

The research and development manager controls a skilled research staff whose size is about 5-10% of the total employment of the firm in all functional areas and he has a number of senior project engineers directly under him who are made responsible for the day to day operations of the various projects which make up the research department's portfolio of projects. The process by which project ideas are generated within the firm is random and the search process for new project ideas is delegated to every project engineer and sales engineer. In fact most project ideas are generated from the research and development staff with a number of improvements in design, i.e. applied design projects, suggested by production engineers. Sales engineers often stumble upon untapped market demands and are responsible for putting firms, who want a special instrument designed and made, in touch with the R & D manager. A few ideas come also from other sub-departments in the firm but the major source is the R & D laboratory itself. Perhaps this is because the firm has a type of rigid structure in which ideas can be communicated and formulas can be calculated to aid decisions. The existence of channels of communication through which ideas for projects can be passed and a "vocabulary" in which facts about them are analysed and formalised allows the research engineer to be aware of the desire of the firm for project ideas but most important that these ideas should be presented in such a way that they will be useful to the R & D manager.

The firm divides a new project idea once generated into four phases of research:-

1) Investigation
2) Laboratory Prototype
3) Production Prototype
4) Pilot Run

The investigation phase is the most interesting because it is at this phase that decisions about possible adoption of projects are made. It comprises three more or less separate stages which will be described as follows:-

A) Preliminary Product Survey

In this stage a broad definition of the technical features of the project is required. In the light of this definition a list of possible technical approaches for the product is drawn up and critical technical areas are identified and evaluated. A preliminary evaluation of the market into which the eventual product will sell and its likely costs are also made. This preliminary survey is generally carried out by the engineer who put forward the initial idea.

B) Detailed Design Study

This presupposes a satisfactory outcome for the preliminary study. The outcome of the initial study is reviewed at a meeting of the R & D manager with the senior project engineers and a detailed study of possible project designs is carried out by teams of research and design engineers to evaluate the one which is most feasible in terms of overcoming major technical problems at a given cost level.

C) Project Proposal

Stage (B) is an essential prerequisite for (C). In (C) a complete technical specification is prepared for the project and where possible preliminary circuit diagrams are provided. Together with the specification is an accompanying formal market estimate, i.e. an evaluation of economic factors and a time schedule for the development project.

This detailed project proposal is most often carried out by a senior project engineer who coordinates the opinions of the project initiator and the research and design teams employed on the project.

Given the structure presented by the firm for the evaluation of projects how are projects reviewed in practice and what factors tend to be given most emphasis in the review procedure? It is important to remember in considering the process of project evaluation that firm A has never yet had a budget constraint on research and development spending, to some extent this is because the firm is not aware of the nature of the relations between R & D, inventive output and economic results but mainly because of the shortage of new product ideas. The firm's growth is limited by the growth of new ideas and, therefore, the firm has adopted the policy of undertaking R & D activity in a limited number of technical areas and planning a concentrated R & D effort in each of these areas in order to highlight new ideas. This policy is further necessary because the shortage of really good engineers means that R & D also has to be an educative process in which the benefits of concentrating are reaped by engineers "learning by doing" and generating new product ideas with increasing momentum through time.

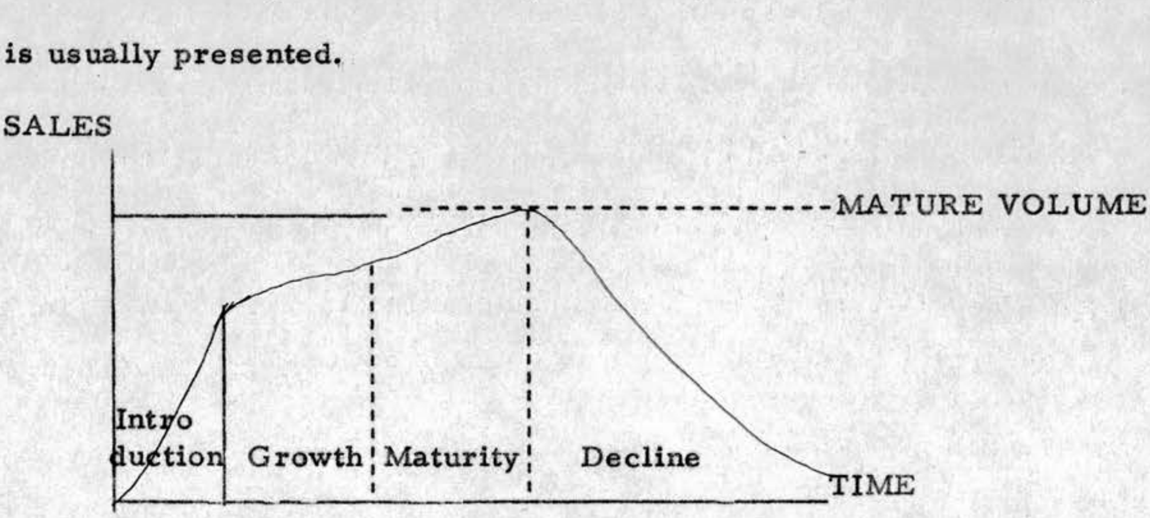
We find that the process of preliminary evaluation of new product ideas is very sketchy and informal and the project initiator's idea is usually taken on trust. It is assumed that the initiator is sufficiently objective that his judgement and experience are a guarantee against the need for a formal preliminary evaluation.

Once this initial review has been carried out by the project initiator, the project idea is passed on to the research manager for action. He generally convenes a meeting of his senior project engineers to evaluate the areas in which greater information about the feasibility of the project is needed. Once the areas are defined a working party of research and design engineers is set up to evaluate the project in detail and this team is encouraged to maintain close liaison with the marketing, sales production and financial areas of the firm. The process of reviewing projects occurs regularly in the R & D department and projects are formally reviewed as and when they are generated. One of the main elements of the formal review is the judgement of the potential worth of a proposed development in terms of financial criteria such as the likely return on the R & D investment. The calculation of such criteria is not regarded as being an end in itself as far as the decision to adopt a particular project is concerned. Occasionally overriding technical or other reasons influence decisions and alter the weighting given to financial evaluations. Yet, financial criteria are given a large measure of credibility by the research and development manager in his project selection decision.

In this formal financial review the working party considers three basic economic factors in relation to a particular project. First, the total money volume to be expected from the product during its life cycle. Second, the likely value of the return on the R & D investment which involves some estimation of the likely costs of the R & D investment. Third, thelikely level of operating profit.

Money volume to be expected from an eventual product is important to a firm because of its production facilities. The firm regards product lines which generate a volume per annum less than some specified amount as not being capable of efficient manufacture by the firm. The criterion of rejection is sometimes flexible if a small volume project can be expected to utilise production facilities common to other lines. The statement that the firm requires product lines which generate sufficient money volume to some extent pre-empts the firm's research and development strategy given the firm's objective of maintaining technical leadership in its field. It is likely that a small number of high cost projects will be the backbone of the firm's R & D effort with high earning, small cost projects being incorporated in order to meet corporate profitability objectives.

Money volume is calculated by separately estimating the eventual price of the product and the sales to be expected over the product life cycle. The first factor that is estimated is always sales and this is done by exploiting the product life cycle concept. The product life cycle[1] is a concept in marketing theory which relates sales as a function of time and usually four stages in the sales history are visualised. First, product introduction; second, market growth; third, market maturity; fourth, sales decline. An idealised shape for the life cycle curve, as in the following diagram, is usually presented.



1. Theodore Levitt, "Exploit The Product Life Cycle" <u>Harvard Business Review</u>, 43, November-December 1965.

Given this shape for the sales phase of the project the engineer and people from the marketing department try to estimate the peak or mature sales volume and the time period over which sales will continue. In this way, they can estimate approximately the parameters of the curve and the sales volume in each phase of the launch. With this knowledge of sales volume the engineer is asked to consider for various price levels in a feasibly profitable range the likely mature sales volume that will occur under each price. This often requires that the engineer has to consult to obtain information on the competition for the product and then subjectively assess the mature volume at prices within the range. The price that gives maximum money volume is obtained by drawing the curve of mature money income i.e. price x sales volume at that price against price and selecting the maximum point of the income curve.

Return on investment is calculated as the ratio between the estimated additional profit contributed by the product during its first five years of useful life and the total engineering development costs. It is assumed that the calculation of additional profit contributed by a new product contains an element to allow for any loss in profits incurred on an existing product which is competitive with or complementary to the new product. However, no allowance is made for the timing of cash inflows or outflows or for inaccuracy in the estimation of these cost and revenue cash flows. Discounting criteria are adopted very rarely and in this firm the major instance has been as a justification for installing a computer facility, a common research overhead for the whole R & D department. Though the payback period, loosely the period over which revenues will balance costs, is not specifically calculated the R & D manager admits that he does a quick calculation to determine the approximate length of the payback period.

Once the return on investment i. e. the benefit/cost ratio has been obtained its value is compared with a corporate or target value for the return factor. The firm requires that the value of the ratio should be as high as possible but in most cases it should certainly have a value greater than four.

Operating profit per unit of a new product is defined by the firm as being the difference between selling price per unit and manufacturing plus selling costs per unit. The definition takes no account of the development costs of a new project. The firm generally requires an operating profit in the range 20-30%. The estimation of the likely level of operating profit is dependent upon a preliminary analysis by the engineer of labour and materials costs, overhead costs and sales and marketing costs in addition to the estimates of price and volume made in the previous return factor analysis.

Armed with the three estimates of money volume, likely return and operating profit that may accrue from introduction of a new project the research manager contemplates the options open to him.

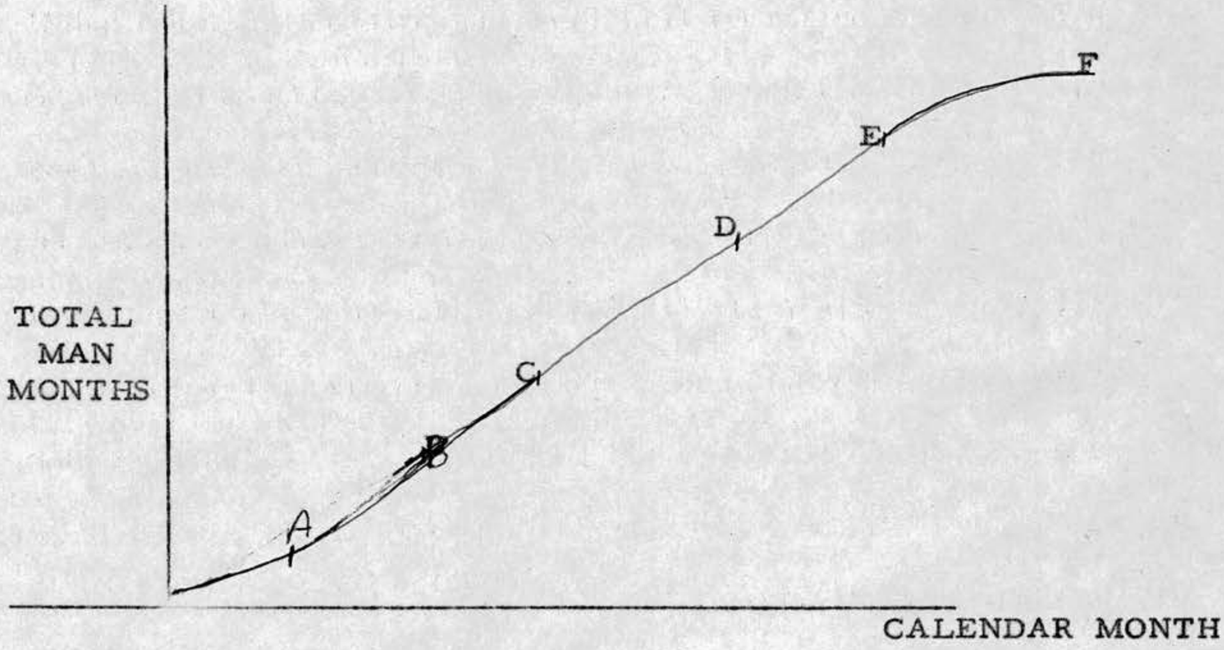
He has immediate authority in the project selection decision and he acts on the basis of the financial and technical evaluation of a project made by the working party. The R & D manager in this firm is conditioned by exposure to an academic research environment in that he favours projects which maintain the company's technical leadership. To this extent he encourages planning of research in a number of technical areas but he is also ruthlessly profit and growth oriented in his outlook. His decision to undertake a project is a rational one always because he does not allow technical merit to overcome sound financial reasons. However, when he takes risks upon a technical idea whose economic future is uncertain he believes in acting upon his hunch about the eventual market and the value of the project to the firm. In this respect his risk taking behaviour can be taken to be sound managerial behaviour in the light of the information available and the goals of the firm.

Whilst the manager does not review projects on a batch basis at yearly intervals, he nevertheless waits until a number of project options have emerged. At that stage the research manager adopts a policy of ranking projects in the order of the attractiveness of their return factor ratios subject to the constraints that they appear to him to be technically sound and meet the criteria of satisfactory levels of money volume and operating profit. The research manager then looks at the ranking and subjectively decides upon the projects he will recommend for adoption to corporate management. He then sends his recommendations on accepted projects to the managing director who either confirms the research manager's decision or reduces the budgets allowable for some or all of the recommended projects. The managing director never rejects a project recommended by the research manager and only makes amendments about the time estimated to complete the work and certain minor financial details. In practice, up until very recently, every project that has satisfied the return factor criterion has been adopted by the firm because it has never exhausted its budget resources for R & D work owing to the shortage of good engineers.

However, at present largely as a result of a far-reaching recruitment policy on the part of the firm its technical capability has been expanded considerably and the firm now faces a difficult resource allocation decision. The injection of new engineers of quality has stimulated the process of idea generation and the number of potential projects is now very large. Funds available for this work, though much larger, are now no longer capable of meeting all demands. As a result of this the formalised selection procedure outlined earlier has now become a major tool in the selection decision and is used rigidly in order to produce a list of worthy projects. Once this list is available, the research manager summons a meeting of the senior project engineers and supplements the mechanical selection criterion with the opinions of his staff. If it is felt that the selection procedure has been too generous to a technically undesirable project the list is amended but this occurs very rarely.

We must note here that our discussion of the selection process has been treated as if the decision to select projects only occurred at one point in time. In fact, projects are considered randomly through time and are compared actively with projects already in the firm's research portfolio. The firm uses several techniques including critical path analysis in controlling and reviewing the progress of projects. Typically, on any project the project engineer holds a series of regular checkpoint meetings at which the progress of a project is reviewed and every six months he is required to submit an updated formal technical and financial review to the R & D manager for discussion. The updated return factor is compared with corporate targets and estimated return factors of new projects. If the project's future looks unpromising the research manager quickly decides to cancel work on that project. There are a number of past cases of projects which have been frozen because of an unpromising future. The research manager regards all past costs as sunk, what is important to him is the expected level of future costs and benefits which he rightly considers to be the relevant costs and benefits for decision making purposes.

Project review is thus an integral part of the R & D process and, in this firm, in addition to updating project data and return factor forecasts as we have outlined, they also plot graphs to show how the progress of a job (in time) compares with the previously planned estimates of that progress. The method consists of plotting two sets of data which are superimposed. The first set of data plotted on the chart is a historical record of the accumulated cost of the project against time. The cost is measured in man-months by deflating actual expenditure figures by a factor which indivates the effective cost of a research employee per month. This factor will clearly vary with changes in wage rates and research productivity. Figure 1 shows the typical shape of the curve of total effort versus time. In the case depicted the number of engineers employed on a project varies through time because effort on a project slowly builds up over the initial period until somewhere in the middle of the project the maximum amount of effort is applied. This reduces gradually as the project nears completion.



A: INITIAL PROTOTYPE

B: FINAL LAB PROTOTYPE

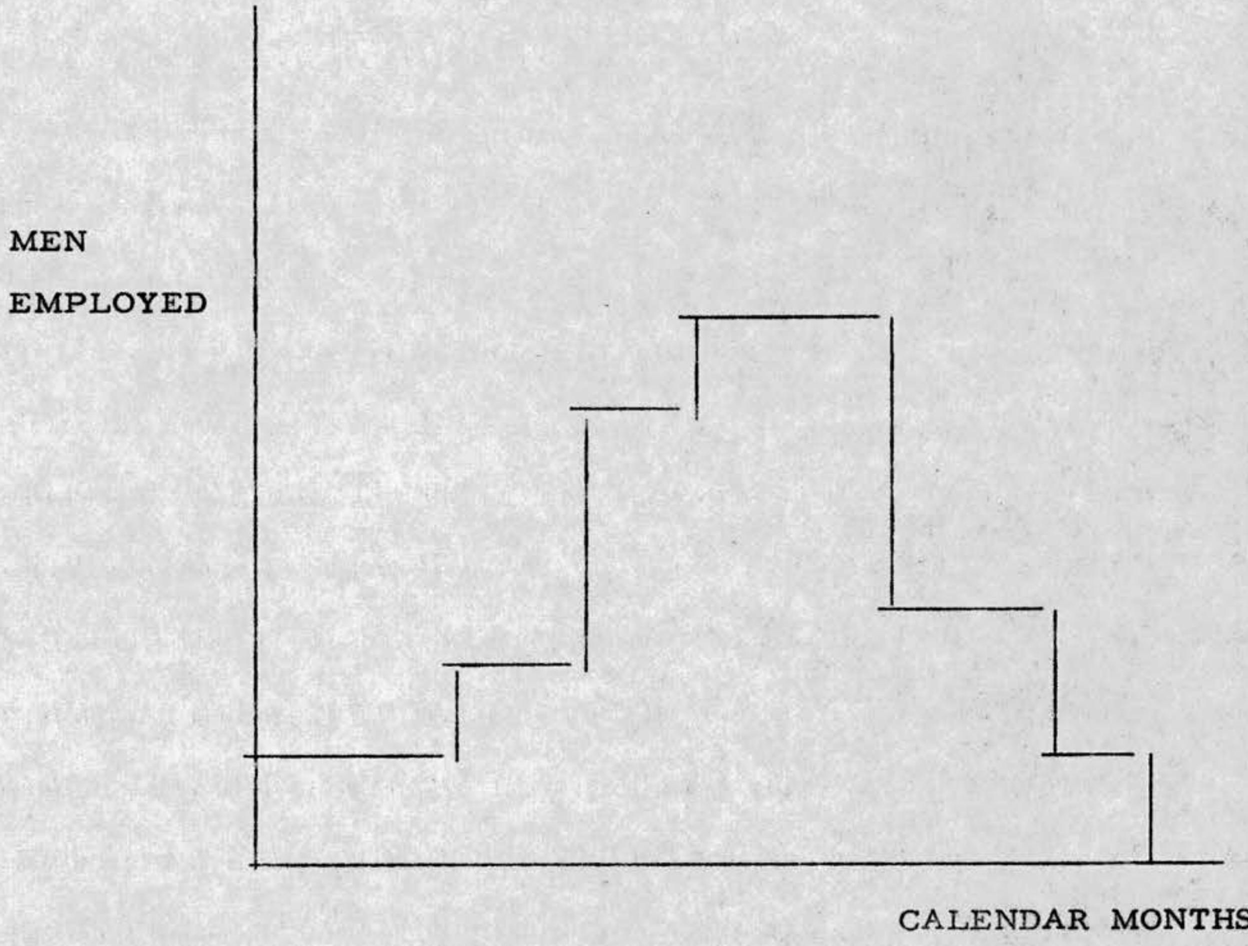
C: PRODUCTION PROTOTYPE

D: PILOT RUN

E: PRODUCTION RUN

F: FIRST SALE

FIGURE 1 (a)



TOTAL EFFORT VERSUS TIME FOR A PROJECT IN WHICH THE NUMBER OF ENGINEERS EMPLOYED VARIES

FIGURE 1 (b)

Note: 1) Scales on the axes are not given because they are not necessary in discussing the nature of the procedure in general terms.

2) The characteristic S shape of the upper curve - 1 (a)

During the course of a project, we know that various stages in a project's development are reached. We can identify the completion of an intitial prototype, a final laboratory prototype and a final production prototype and then the beginning of the pilot run, production run and sales phases of the project's life cycle. We can plot these stages on our S shaped cost curve in figure 1 (a) which will show for us the costs and dates by which the given stages will be reached viewing the project a priori. We can also plot the project stages by marking the values on the cost and time axes as in figure 2.

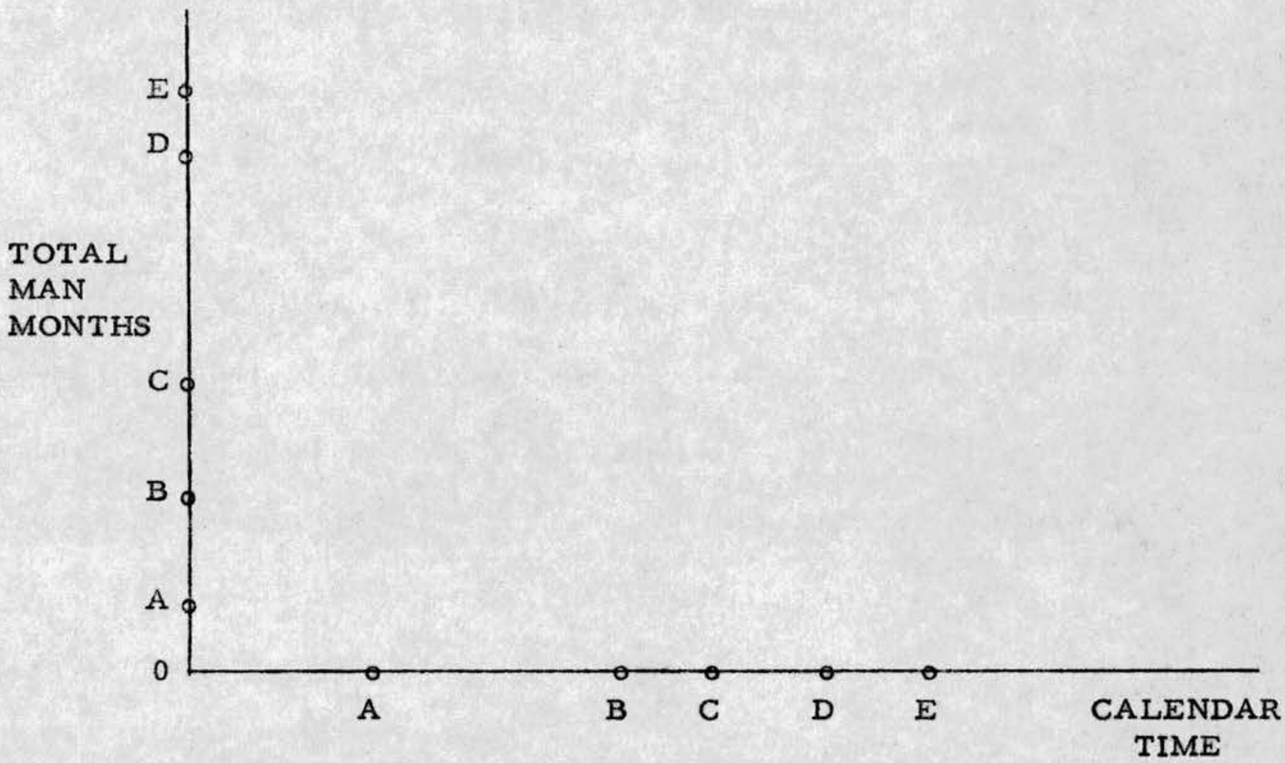


FIGURE 2

Note: - the definitions of A, B, C, D and E are the same as in Figure 1

After some interval of time let us assume that some information on actual cost expenditures (man months) becomes available. We can plot this point on a curve (0^1) as in figure 3 and treat it as a new origin from which two sets of axes emanate and on which new estimates of target dates and costs for the various stages are made.

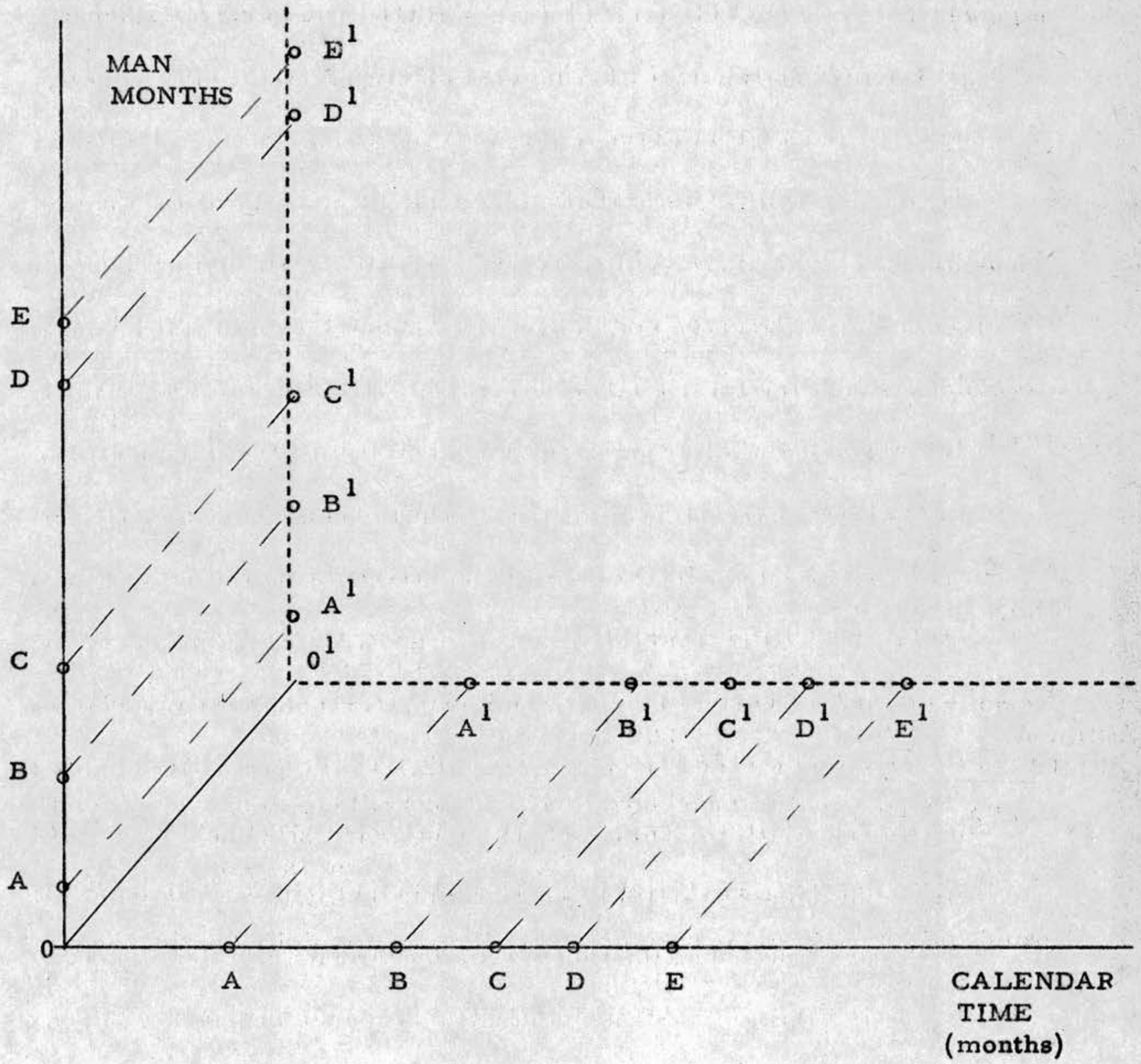


FIGURE 3

In Figure 3 we have contructed a situation in which we have not yet reached stage A of the project. Our new estimates A^1, ---, E^1 reflect our present assessment of dates and costs for the completion of the various stages. The new estimates are joined by short lines to the original estimates A, ---, E. The fact that these estimates are not parallel to the axis indicates that our performance has slipped with respect to our estimates. The chart is updated in this way periodically and its shape shows the extent to which we are meeting prior time and cost objectives. As a control tool it is used primarily by the research manager in updating his knowledge about projects and aiding him in any further project resource allocation decisions. Critical path analysis is used by engineers in the project teams so that they meet time objectives in their engineering work.

Having thus outlined the rigid decision making procedures of Firm A we must make some comments about formalised procedures of this type. Many engineers in the firm admit quite freely that their estimates of cost and sales volume for projects are often biased in order to make the resulting return factor estimates appear favourable to the firm. They point out that the procedures themselves are very inaccurate and do not incorporate technical factors which are often not understood by finance or marketing executives. Therefore, engineers deliberately amend estimates in order to make return factors acceptable to the firm. They do not do this for personal reasons, e.g. scientific attractiveness. Their sole motivation is to make the firm move towards the adoption of more flexible numerical criteria for differentiating between projects. For this reason they were very keen to cooperate with the research work outlined in Part IV.

We turn now to a consideration of Firm B. The strategy of the firm in the research and development field has not been clarified by means of a statement of objectives for R & D. It can fairly be said, however, that the firm can be described as a research follower rather than a leader. The firm tries to spot gaps in the field of electronic instrumentation and having found them attempts to develop an instrument subject to the availability of the required technical skills in the laboratory. The firm has a number of technical areas in which it has accumulated expertise over time and is in fact divided organisationally into groups working in each of these areas. However, despite its concentration on a number of technical areas the firm has not managed to maintain periods of technical leadership in any of them for a significant proportion of the time.

There is clearly a contrast between Firm B and Firm A. Firm A has an organisation structure with a considerable degree of decentralisation and the establishment of managers with responsibility for the various financial areas of the firm's operations. Authority is delegated from managing director to departmental manager and the span of control is wide. Firm B has a pyramidal type of organisation structure in which any decision of consequence is referred back to the managing director. Recently, this firm has achieved a certain measure of decentralisation as a result of the establishment of a technical manager, marketing manager and financial manager who oversee their particular areas. Yet the managing director tends to pay lip service to decentralisation and still possesses ultimate authority. The firm is clearly in the process of moving towards an organisation structure most suitable for its stage of development. There are, for example, strong feelings about lack of communication between engineer and manager in the firm and no established channels through which communication can easily be effected.

Research and development in this firm is thus carried out without a real sense of the ultimate objective and in this sort of environment frustrations build up between engineer and manager. Ideas for research projects tend to be generated mainly by customers. Other sources for research ideas are the production engineers who suggest redesigns of existing instruments and the research departments themselves who generate a smallish number of research ideas. The orientation of the research and development work is applied research and development directed towards new or existing products. Any fundamental research work is not approved by the firm unless outside sources of finance, e.g. IRC, NEDC, AEA etc. can be persuaded to provide the major proportion of the capital investment at risk. It is not surprising that the mix of research and development work carried out by the firm is so diverse and loosely planned in view of the type of organisational communication and authority delegation that exists at present. The research and development strategy is to operate in the market to fill gaps in instrumentation technology and to provide low cost high quality instrumentation. Any major technical development in the firm is either gained by buying technological expertise in the form of men or research results from other firms or from outside sponsorship of high risk projects.

When ideas for R & D projects are generated within the firm there is no involvement in committee procedures for reviewing their feasibility. It is assumed that the idea source is sound enough for any preliminary review to be dispensed with. The firm sets aside a maximum amount of money that can be used to support research and development work in any given year (although it is never sure about how much to allocate) and projects are reviewed for adoption in the light of this budget constraint. Projects occur randomly within the annual period and no attampt is made to wait for the really good project or to review projects on a batch basis. A project is formalised very roughly in a meeting between the technical manager and the marketing manager and a private venture proposal form is completed. This form requires a brief description of the likely specification of the final product, a rough quantitative estimate of the product's likely development cost, a qualitative assessment of the likely market and a time estimate for completion of the work. Once this form has been completed no attempt is made to compare it with any other forms available for other potential or existing products, it is merely transmitted to the managing director for a decision on acceptance or rejection. The managing director has established a priority for undertaking projects that are a result of a customer's idea because they have greater possibilities of immediate financial returns. He is not at all concerned about existing projects because whatever happens they are always completed and introduced in the market. Also, the managing director tends to be keener on supporting projects, whatever their merit, at the beginning of a financial year when expectations are higher than at the end when priorities are often shifted to maximising productive output in order to produce a favourable financial statement. Money has been a constraint on the expansion of research and development work because more projects have always been available for development than resources to support them. Yet, despite all this, the firm has managed to grow quite considerably over the last five years with its strategy of being a technical follower in its own research and development work and this may reflect the managing director's decision making ability. Future growth, on the other hand, may be inhibited if the present policy of a low cost, high spread diversified research portfolio fails to produce a future stream of new product research proposals of sufficient calibre. From the role of participant observer it is clear that efficiency will be maintained in the future if attempts are made to reduce the frustrations and tensions built up within the firm because of the poor communication between engineer and manager. It is still possible that a loosely organised decision structure will be preferable for the firm but some changes are necessary in order to ensure that the participants in the system know their roles and functions.

4.4. Summary

The description of the decision systems for Firm A and Firm B has been undertaken to provide a basis for our understanding of the R & D process. It is clear that decision systems that are either too loose or too rigid generate problems which are equally difficult to solve. A compromise between the two in which the rationality of the rigid and loose elements is apparent to all personnel in the firm may be a good compromise.

Our knowledge about the R & D process has been enriched because we note that whatever the firm there are common elements:-

a) The determination of the budget for research and development

b) The search process for possible R & D projects

c) The preliminary elimination of infeasible projects

d) The appraisal of a project's value

e) The decision about acceptance of a project

f) The changes in R & D projects through time and the general uncertainty characterising the R & D process i.e. technical uncertainty about a project's feasibility and commercial uncertainty about its viability and performance in the market place.

Therefore, economic allocation decisions have constantly to be made in this sort of technically uncertain environment. The manner in which these decisions were executed in firms A and B differed mainly in terms of the information required and used by the decision maker in each case. There is, of course, a difference in the organisation structure and in the turnover of each firm, with firm A being the more financially viable. In firm A the decision maker's goals were more of less in line with those of the firm and he approached the problems of allocating resources to projects in a logical and rational manner. In this allocation process he was guided by the generation of detailed information, both financial and technical, on each project at the initial stages and at points throughout the project's life. The decision maker in B, the managing director, had the goals of the company and his own goals in one to one correspondence and his decision making was very informal with strong reliance on personal judgement. It is fair to say that both decision makers have been very successful because their projected objectives for growth in economic terms have been met. Despite the ability of the decision maker in B the view is taken here that the provision of information of an economic and technical nature about an R & D project helps decision making because the manager has more time and a better framework with which to make his decision. On the other hand, information cannot replace decision and neither can any formal methods. The function of a decision structure and a model is to provide information and an analysis of possible alternatives as accurately and logically as possible.

Its function is not to replicate the processes of decision because these are individual to the decision maker and a function of his own perception and goals. Yet, the provision of a thorough economic and technical analysis of problems will tend to improve decision making by identifying valuable projects and thus allow the decision maker to adapt to a changing and uncertain technical environment.

Let us return to a consideration of the decision maker's objectives. There is no evidence from these two decision makers that they act as if to satisfice. They seem from observation and deed to act so as to maximise long term profitability and growth for their firms. However, the statement in the previous sentence requires some qualification. Whilst, we consider that it is impossible to justify our assertion that the decisions makers in A and B behave as maximisers by any objective test, we nevertheless believe that the weight of evidence is consistent with our assertion. Both firms are successful and have grown quickly over the past five years. The rate of growth of profitability and sales has been significantly large in both cases. Both decision makers showed profit consciousness; the decision maker in A cancelled projects which looked unprofitable whilst the decision maker in B altered the allocation of financial resources for R & D in the second half of the financial year in order to improve the firm's end of year financial statement.

In Part IV of the thesis, when we try to evaluate the decision maker's objectives, formally, some additional evidence will point to the reasonableness of a maximisation objective.

Finally, we should remember the discussion in Chapter where we quoted some theoretical evidence to support the view that the single objective maximisation hypothesis is preferable to the satisficing hypothesis.

Summary for Part II

The role of the case study of the decision process is to improve our knowledge of the factors that are relevant to a decision maker in his decision making and to assess the extent to which the routine data and information provided by the firm help him in his decision making. We have seen that decision making is a function of the personal logic of the decision maker and the information available to him. The approach here is to assess the information and environment needs of the decision maker so that we can reduce the decision making function to a logical evaluation of alternative outcomes analysed within the firm's own information system. By reducing the decision maker's tasks and his need to be an information analyser we hope that he will make good decisions i. e. decisions based on the logical and reasonable evaluation of all possible alternatives.

It is clear that the research method of participant observation and interview adopted in Part II does not give us much information on the results of historical R & D decisions. This means that we do not know whether logical decision making in the past, which we have evaluated here, has led to good or bad outcomes. There is clearly no reason why good decision making should necessarily lead to good final outcomes because the processes of prior evaluation of a particular project by a decision maker and of its actual operations in practice will clearly differ. In part III we complement the analysis of this part by retrospectively analysing a number of historical project decisions. If from this we find that in some cases "good" or logical decision making has led to poor eventual outcomes for projects we may consider that we can isolate the features of the decision process information systems which contributed to the poor results. In other words information (or rigid) processes to aid decision making may create an environment in which efficient and logical decision making is hindered.

Duckworth[1] quotes Sir Solly Zuckerman who has pointed out that attempts to plan and predict research progress can stifle its creativity. This is clearly an important point because, as we have stated in contrasting the different information and control systems existing for R & D in firms A and B, we do not know whether rigid or formal procedures for decision making in the firm will be beneficial in terms of producing better outcomes and efficiency. We do suspect, however, from our analysis that the extremes of rigid and loose decision mechanisms each have their deficiencies in terms of the environment of the individual firm. A compromise arrangement of a system in which information is processed regularly and efficiently and in which communication between engineer and manager is smooth and simplified is likely to be most efficient without stifling the creativity of the individual engineer.

In our analysis of the decision process we have learnt that it is characterised by the following phases:

1. W.E. Duckworth, "The Determination of Total Research Effort", Operational Research Quarterly, Vol. 18, No. 4, 1967.

a) Search for possible research opportunities

b) The formal or informal evaluation of research opportunities

c) The determination of the level of the R & D budget

d) The comparison of alternative research opportunities and the selection of the ones with greatest potential

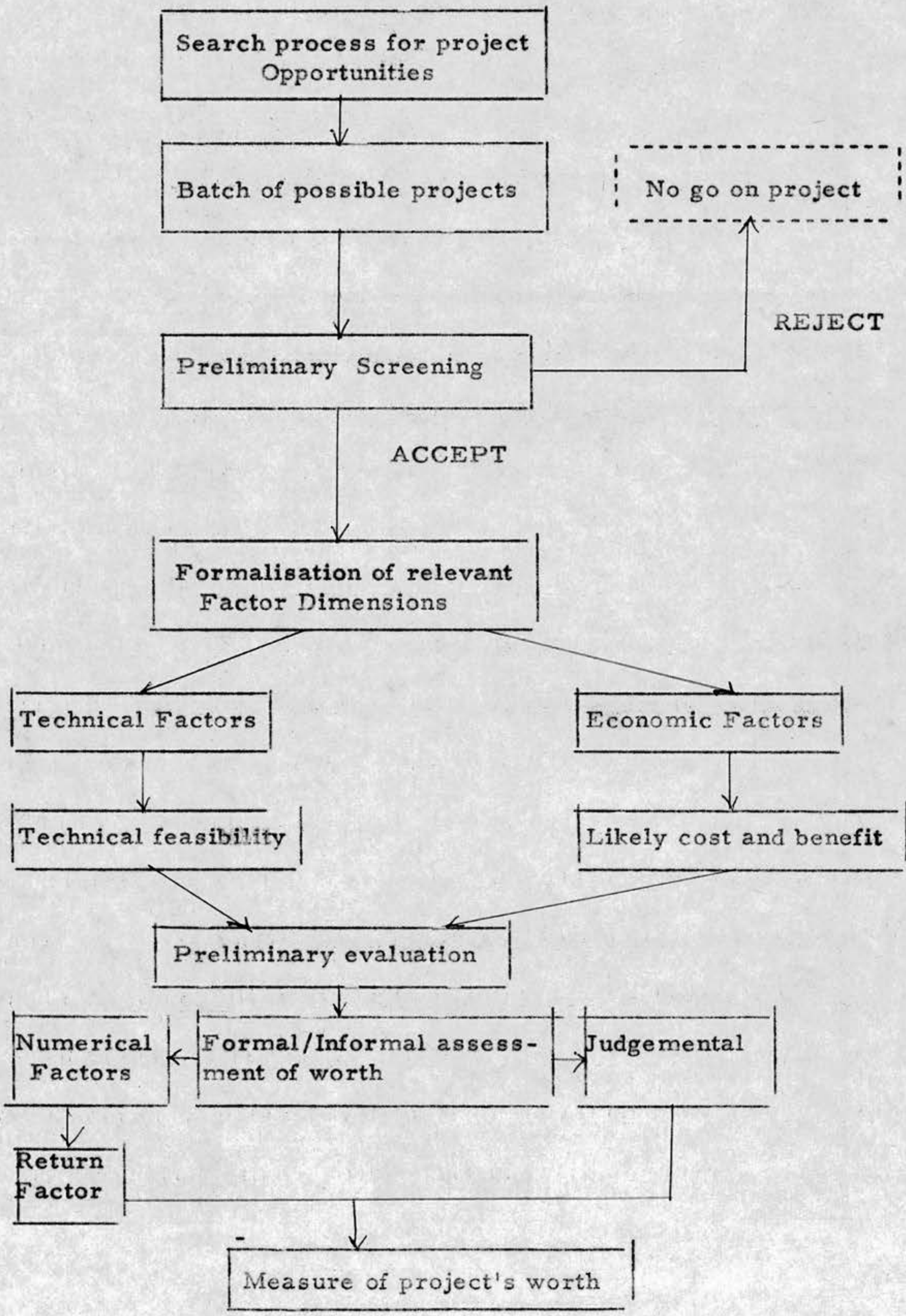
e) The constant re-evaluation of existing and newly developed R & D projects for control and comparison purposes

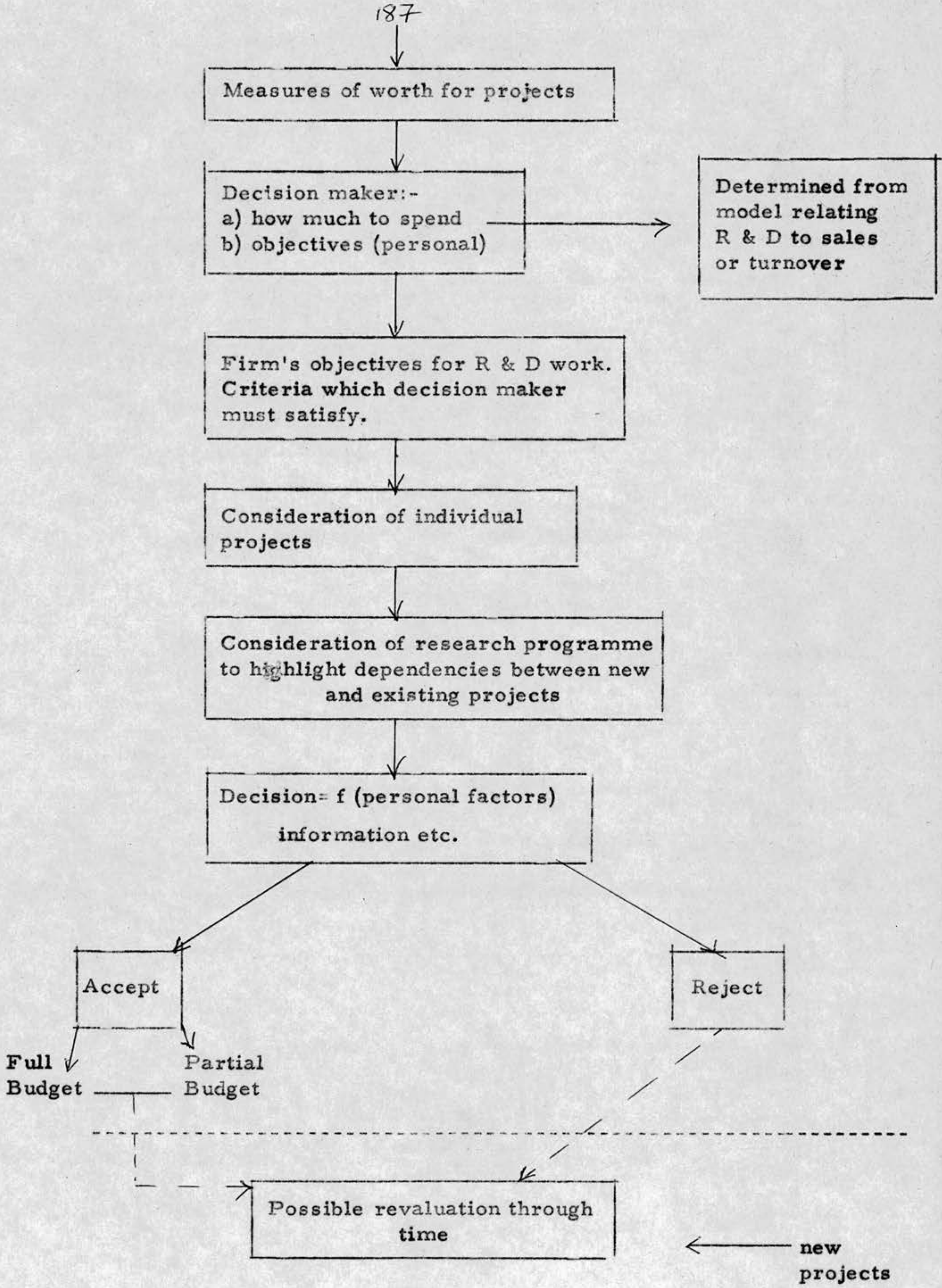
We can characterise the formal structure of the R & D process and a general type of decision mechanism by considering the following block diagrams.

The diagrams should serve as a quick representation of the processes of search for, evaluation, comparison and selection of research projects. This framework is crucial as a building block for the later model building analysis.

STAGE 1

Evaluation Stage of R & D Process Depicting a General Decision Making Procedure





STAGE II OF DECISION PROCESS: - DECISION STAGE: - COMPARISON AND SELECTION OF PROJECTS AND RESEARCH PROGRAMS

Chapter 5

PART II

AN ECONOMIC ANALYSIS OF THE INFLUENCE OF RESEARCH AND DEVELOPMENT ON THE ECONOMIC RESULTS OF THE FIRM

5.0 Introduction

We have seen in Chapter 4 that the decision maker in R & D in Firm A has a large amount of information on which to base his decisions. We suggested that the provision of accurate and realistic data was necessary for good decision making in R & D in general. Yet we pointed out in our analysis of both firms A and B and in our initial literature review in Part I that a great deal of vagueness surrounds two problems. First, the problem of how much to spend on research and development and second, the general nature of the relationship between research and development effort and financial performance of the firm. In this chapter we try to understand with the aid of the limited amount of data available from A and B the essention nature of the relationships between research results and economic results. We regard this relationship as being the most important and if its nature can be determined we can then suggest how much should be spent on R & D. We approach our analysis by briefly considering previous research in the literature and follow this by presenting the results of our treatment of the problem.

5.1. Literature evidence

We shall divide this review section into two parts. We shall first consider the references on the determination of the level of research expenditure and then consider references on the relation between research expenditure, inventive output and commercial results.

5.1.1. The determination of the R & D budget for the firm

W. E. Duckworth[1] in a recent paper looks at the question of how much money should be spent on R & D at the firm level. He considers two main approaches which can be useful. First, to determine the levels of research expenditure by looking for relationships between company or industry performance and total research and development expenditure in the firm. Second, to make the determination by adding up the amounts of expenditure necessary for each of the component parts of the R & D mix e.g. basic research and applied research towards new products or processes.

Examples of the first method are the analytical and comparative approaches. Hart[2] puts forward an analytical technique in which the maximum amount of expenditure that the firm can justify for its R & D operations is determined. He considers first the factors that affect the obsolescence rate of existing products, and therefore, of R & D spending. In order of their importance they are as follows:

---

1. W. E. Duckworth, "The Determination of Total Research Effort", Operational Research Quarterly, Vol. 18, No. 4, (1967)

2. A. Hart, "Planning for Increased Research Productivity", Productivity in Research, 1963 (London:- Instn. Chermical Engineers)

1) The extent of competition

2) The nature of the product

3) The nature of the production process

4) The availability of resources in research and production

5) The productivity of the R & D department

6) The size of the firm

He then develops a method for forecasting the maximum amount of research expenditure by first assuming that if R & D expenditure were stopped today the profitability of the firm would fall to zero over a number of years depending on the obsolescence rate of its products. He then requires that several people in the firm give estimates of the period of future life of the company, i.e. positive profits given no R & D, and the rate at which profits will decline to zero. Finally, he tries to compare the effects on profits of the situations with no - R & D with those in which R & D is continued in the future at an economic rate (gross profit being assumed to remain at its present level for all years from now on into the future). His analysis can also be generalised to compare the effects on profits of no - R & D situations against situations in which R & D grows at x% per annum where x is some positive value. Basically, the method of calculation is the same in both cases and entails determining the discounted profit at the firm's cost of capital for the R & D and no - R & D situations. If we call these discounted profit values P_1 and P_2, the maximum expenditure justified on R & D is defined to be $(P_1 - P_2)$.

It must be noted, therefore, that Hart's method allows us to set an upper bound on the amount we should spend on research as a whole and, if necessary, the analysis can be carried out on each single project to determine the upper bounds on budgets for individual projects. It is, however, heavily dependent on the production of sensible estimates of the rate of decline of gross profit over the remaining life of the firm in the no- R & D case. Hart argues that it doesn't matter if these estimates are subsequently proved wrong because they represent a realistic view of the present state of knowledge of the future and since the situation changes through time such forecasts can also be revised. This is all fair enough if we accept that any employee in the firm can give a realistic estimate of profit decline over the next 5-10 years in a situation in which one of the essential features of his firm, its R & D work, no longer continues. Such a forecast much clearly neglect any attempts that the company may make to alter its status and role after R & D work is given up.

Thus, Hart's maximum expenditure (MEJ) figure is to be regarded as a guideline with which to evaluate the exact amount of R & D spending. It is clear that it could be used to give guidelines or MEJ for each of the categories of research in the firm and help provide an answer to the budgeting problem by summing a series of smaller categories to get the total. This assumes that a meaningful distinction can be made by the engineers in the firm between basic and applied research of various kinds. It is by no means clear from firms A and B in our study that they can meaningfully distinguish between the research categories outlined in the first page of the questionnaire.

Having looked at one analytical approach which can be used to solve the budgeting problem as a whole or as the sum of distinct parts, we consider the meaning of Duckworth's comparative approach. This method requires that we search for data that give us guidelines on the relative amounts spent on R & D in our industry and typical rates of growth of firms in that industry. Useful data sources for this type of information are the FBI Survey and the recent government enquiry on R & D which are noted earlier in this Part. However, the major difficulty with comparative exercises ~~exervices~~ of this type is that they assume that one of the firms being compared has solved the problem of how much to spend on R & D.

Duckworth's final suggested approach is to calculate the research and development budget as the sum of the separate budgets required for the different categories of research - fundamental, applied - offensive, i. e. new product oriented and applied - defensive i. e. existing product oriented. This is apparently the method used in most British companies though we are not told how budgets are calculated except in the case of offensive research where it is suggested that the controlling factor in the cost decision is the availability of capital to exploit the research.

It can only be said that none of the approaches given by Duckworth solves the basic problems of how we determine budgets for R & D and the spread of those budgets across the various possible categories of research work. Hart's analysis though rough gives us an upper ceiling which is so large given the present levels of R & D budgets as to be almost useless to the individual firm. Developments can only be made in the budgeting problem by returning to the factors which should determine R & D spending at the level of the firm and trying also to understand how research and development affects economic results. It seems that our lack of understanding of the process of innovation inhibits us in our analysis.

5.1.2. The Relation between R & D Results and Economic Results

Mansfield[3] in a very important study provides us with a sophisticated quantitative analysis which brings R & D budgeting quite correctly into the general area of the relation between R & D and economic performance of the firm. His main concern in the study is to investigate the determinants of the level of a firm's expenditures on R & D. He finds that the level of a firm's research expenditures can be explained reasonably well by a model in which it is assumed that the expected rates of return from promising projects follow the Pareto distribution. Given this assumption the determinants of the firm's desired level of R & D expenditures are the distribution of

---

3. E. Mansfield, "Industrial R & D: Determinants and Relation to Size of Firm and Inventive Output", Chapter 2 in Econometric Studies of Industrial Research and Technological Innovation (W. W. Norton, 1968).

expected rates of return from R & D projects and the firm's size. He further finds that the firm's speed of response toward this desired level depends on the extent to which the desired level differs from last year's spending and the percent of its profits spent last year on R & D.

He also uses this model to forecast R & D expenditures for a given year by substituting the relevant values of the independent variables into his equation for the level of R & D expenditures.

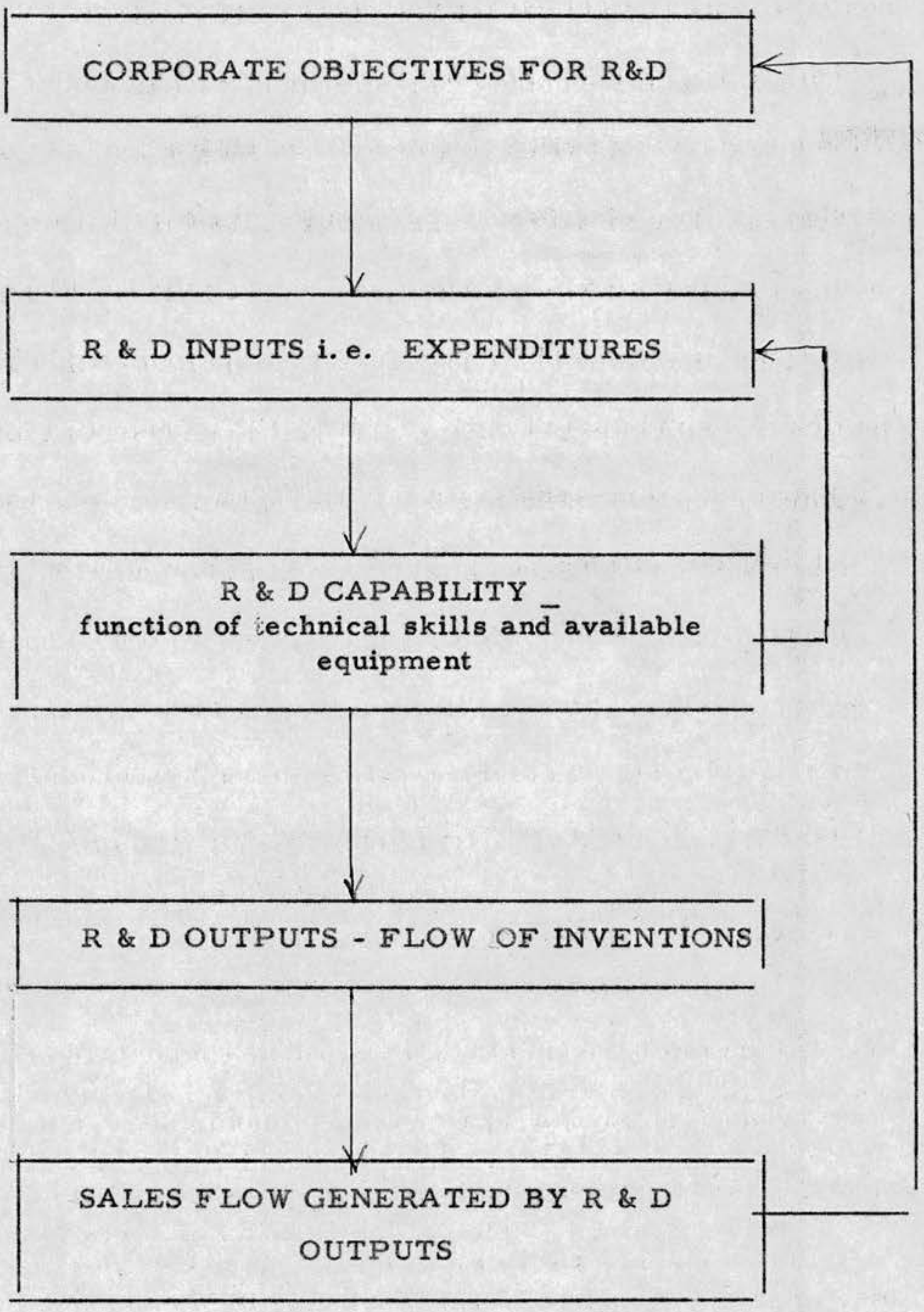
We cannot hope in our analysis to match the subtlety of Mansfield's work. However, with the financial and other relevant information which was obtained from the answers to the formal questionnaire, we try to develop some relationships between R & D expenditures and economic results. We turn to this analysis now.

5.2. The Analysis of the R & D Expenditures and their Effect on Economic Indicators of the Firm

5.2.1. Introduction

The model which provides the basic framework for the economic analysis is the classic invention - innovation view of the R & D process. Simply, this is that R & D inputs generate a flow of research or inventive output which is transmitted into commercially saleable products by the economic processes of innovation and risk taking. Our model could be depicted in the form of a block diagram as follows:

MODEL OF THE R & D PROCESS IN THE FIRM



It should be noted that there are other factors determining corporate objectives for R & D, and the firm's R & D expenditures and capability. Some of these such as the nature of the product, the dynamic nature of technical change were spelt out clearly in Hart's study. Further, we do not get involved in arguments which exist in the economic literature about whether or not inventions are generated within the economic system. For the individual firm the aim underlying R & D work is to create new or improved products and thus help to increase the sales and profitability of the firm. It can be seen, therefore, that this simple model corresponds to the realities of the R & D process in the individual firm. The factors not considered by the model such as the nature of technical change can be handled with either methods of analysis and thus aid the further understanding of the economic relationships in R & D. We include here only those variables which are both realistic and important in explaining the effect R & D has on the overall economic position of the firm.

5.2.2. Methodology and Hypotheses

5.2.3. Data

The data used in this study was obtained in the information gathering phase of the work in firms A and B. It consists, in the case of firm A, of information on pre-tax profits, net sales, the total wage bill, capital expenditure, research and development expenditure, marketing expenditure and the number of research and development staff for each of the last seven years. This means that we have only seven observations on each variable in firm A and six observations on each variable in firm B. The limited size of the data base inevitably means that complex and/or sophisticated analyses of the relationships between R & D and economic results cannot be undertaken.

5.2.4. Equations Relating R & D to economic results

For these reasons the method of analysis adopted here is linear multiple regression analysis. Initial linear and rank correlation analyses confirmed that there were strong degrees of association between R & D expenditures and net sales in money terms (which is a reasonable measure of turnover) the eventual output of the R & D. However, these analyses cannot give us the direction of causation between the two variables and we take the position here that changes in R & D expenditures lead to changes in sales rather than vice-versa. It is quite clear that a case can be made that good economic results will lead to corporate management authorising a larger future budget for research and development. In this sense the feedback mechanism that is in operation in the process means that R & D = f(sales) rather than sales = f(R & D). Whilst this influence of increased sales on management's desire to do more R & D does occur, the formulation sales = f(R&D) can be justified by considering what would happen if research and development expenditures were curtailed and completely stopped. The effect over the long term would be a sales decline because the products without R & D would not remain competitive in the market.

Therefore, our first hypothesis is that R & D expenditures influence the economic results of the firm. In making this statement we accept that other variables affect economic results but we do not take account of them in our initial hypothesis. We try to give this hypothesis operation meaning by considering various alternative functional forms for the equation relating R & D to sales. Specifically we consider first relationships of the form.

$$S_{ti} = a + b R_{(t-\alpha)i} \quad ------ (1)$$

where

S_{ti} = net sales in year t for firm i

$R_{(t-\alpha)i}$ = R & D expenditures in year $(t-\alpha)$ for firm i

for $\alpha = 0(1)3$, $\left\{ t = 1(1)7 \text{ for A}, \ t = 1(1)6 \text{ for B} \right\}$, $i = 1(1)2$.

These formulations relate sales in period t to each of the R & D expenditures in t, t-1, t-2 and t-3 separately. The rationale for the formulations comes in part from the work of Palda[4] and Stigler[5]. Palda's study starts from Stigler's premise that the effects of advertising are cumulative and that an advertising message sereral periods ago still has some effect in the present period. Thus Palda views sales in period t as being a function of advertising expenditures in periods t, t-1, t-2, etc. i.e. $S_t = f(A_t, A_{t-1}, A_{t-2} ----)$. Similarly, here it is considered reasonable to regard the effects of research and development expenditures on sales as being cumulative because

---

4. K. Palda, The Measurement of Cumulative Advertising Effects, Prentice-Hall (1963)

5. G. Stigler, Price Theory, Macmillan (1967)

of the phenomenon of technical spin off within the firm. This simply means that the value of a significant piece of research work carried out in some previous time period has an effect on sales for a far longer period of time than initially envisaged. In any case, the relationship of research expenditures ~~on~~ to sales has an inherent lag structure because of the time delay between research expenditures and eventual outputs*.

We further amend the relationships of the form (1) by considering sales to be a function of research and development expenditures, marketing expenditures (M) and technical capability (C) i.e. S = f(R, M, C) and estimate regressions for all possible combinations of the independent variables included lagged independent variables subject to the constraints of the estimation procedure. In general, therefore, we consider relationships of the form

$$S_{ti} = f(R_{(t-\alpha)i}, M_{ti}, C_{ti}) \quad ---- \quad (2)$$

where M_{ti} - marketing expense in period t for firm i

C_{ti} - technical capability in period t for firm i

Our measure of technical capability is given in money terms and is the salary of the research and development staff. This measure is used because in a market context the value of an engineer is measured by his wage rate. Since skilled engineer shortages exist in the area in which A and B operate, it is further contended that the wage rate will measure the good engineer, and , therefore, skill

---

* Note: It can be argued that, since the level of R & D expenditures is often determined as some constant proportion of sales, R & D is a function of sales. In the case of firms A and B no evidence was found to suggest that R & D has a constant proportional relationship to sales.

because both A and B are willing to pay a good salary to the right type of engineer. Therefore, the amount of money spent on technically skilled labour is a measure of the pool of labour skills available to the firm especially since the age structure in the R & D staff in both A and B is young with relatively few highly paid older engineers around to bias the measure of the amount of labour costs for R & D as a measure of the pool of technical skill and capability. This measure, of course, neglects the influence of equipment availability and technical facilities in the firm and thus our measure of technical capability is conservative. We assume, however, that each firm will make available sufficient amounts of technical equipment in order that the engineer will be efficient and productive. We make allowance for the effect of capital and equipment expenditures on sales in the later analysis.

We could have measured technical capability each year in terms of the average number of professional researchers employed by the firm in a given year. This information was obtained from both A and B but in this case the measure of the number of researchers times the wage rate was favoured because the money wage is a weighting mechanism to measure the worth and thus the skill of the individual engineer. Further, merely measuring technical capability in terms of the number of researchers makes this measure conservative because no allowance is made for technical facilities which affect capability as we have said previously this is equally true of labour costs as a measure of technical capability.

Thus far we have outlined the form of the equations relating R & D to sales. We carried out a further transformation on both sets of equations (1) and (2) and this was to transform the original variables into logarithmic form. This type of transformation has the effect of making the relationships more linear and the models (1) and (2) are not then additive models in the variables but multiplicative i. e.

1. becomes $\log S_{ti} = \log A + b \log R_{(t-\alpha)i}$

$$\text{or } S_{ti} = A R^{B}_{(t-\alpha)i} \qquad \text{------ (3)}$$

2. Becomes $\log S_{ti} = f(\log R_{(t-\alpha)i}, \log M_{ti}, \log C_{ti})$

$$\text{or } S_{ti} = K R^{B}_{(t-\alpha)i} M^{D}_{ti} C^{E}_{ti} \qquad \text{------ (4)}$$

Equations (1) through (4) thus summarise the equations we have estimated by regression analysis in order to establish the relation between R & D expenditures and economic results. We must make one further general comment about using sales as a measure of the economic results of the firm. Strictly speaking the correct measure would be a value added variable incorporating the sales data but since the sales variable, net sales, was a measure of actual revenue received in that period it was considered to be a reasonable measure for the economic results variables. However, in order to allay any subsequent criticism equations 1-4 were re-estimated with the variable P_{ti} - net profits before taxes in a given year - replacing S_{ti}.

5.2.5. Input-output analysis

A final very tentative analysis was carried out to relate the variations in particular types of R & D inputs, i.e. labour and equipment to sales. The form of the equations was as follows:

$$S_{ti} = A\, C_{ti}^{B} K_{ti}^{D} e^{\gamma t} \quad \text{-------------} \; (5)$$

where S_{ti} is as previously defined

C_{ti} is the labour costs for the R & D staff per year as previously

K_{ti} is the equipment and capital cost for the R & D department per year where $e^{\gamma t}$ is a trend term to measure technological change. A, B, D are constants

It was only possible to estimate equation 5 for firm A because it proved impossible to obtain a meaningful breakdown for capital and equipment expenditure on R & D in Firm B because of the absence in that firm of an R & D department and hence a natural sub-unit for management accounting purposes.

In the place of the disaggregate analysis of the effects of R & D inputs on output i.e. sales, we decided to carry out a very simple naive model analysis of the relation between output i.e. sales and resource inputs of labour and capital for the firm as a whole. Such an analysis will give us a feel for the differential total effects of the of the resource inputs for the firm as a whole. The equations estimated were of the following form:-

$$S_{ti} = A\ F_{ti}^{\ B} L_{ti}^{\ C} e^{\gamma t} \quad \text{------------} (6)$$

where F_{ti} is the total wage bill for the firm as a whole per year

L_{ti} is the total capital expenditure excluding depreciation for the firm per year

and S_{ti} and $e^{\gamma t}$ are as previously defined.

We turn now to a discussion of the methods of estimation used in the analysis.

5.2.6. Methods of Estimation

It should be noted that we require an estimation method to determine the nature of the relationship between a dependent variable, sales, and a series of independent variables. We naturally think of regression analysis but it is important to remember the limitations of such an analysis. It assumes, as all analytical methods do, that the underlying relationship has been correctly specified. In this case our specification is in terms of linear or log-linear models. This is considered to be the best compromise with the limited amount of data available. If the data base were much larger then the nature of the relationships would be more evident a priori and we could use possibly non-linear models to specify the relationships. Given, however, that the equations (1) - (6) are assumed to be correctly specified we estimated their parameters by means of ordinary least squares.

The method of least squares, together with all its important assumptions, will now be outlined. Let us assume that each equation can be written in the following form:

$$y = XB + U$$
$$(1 \times 1) \quad (1\ xk)\ (kx1) + (1x1)$$

Where B is the column vector of regression coefficients $\begin{bmatrix} \beta_1 \\ | \\ \beta_k \end{bmatrix}$

X is the row vector of independent variables $(x_1, ------x_k)$

y is the dependent variable

U is the random or error term

The assumptions of least square analysis are as follows: first, the elements of X are fixed constants; second, the u's have zero mean, and are uncorrelated with constant variance i.e. $E\ (U) = \underline{0}$, $E\ (UU^1) = \underline{6^2 I}$. The principle of least squares (LS) is to minimise $(y - \underline{X}b)^1\ (y - \underline{X}b)$ to give $b = (X^1X)^{-1}X^1y$ as the least squares estimates of the β. Under all these assumptions the Gauss-Markov theorum tells us that b is the best, linear unbiased estimator of β. But, in practice the LS assumptions are frequently invalidated.

First, X may be a matrix of random variables. However, a conditional analysis $E\ (U \mid x)$, $V(U \mid x)$ will validate LS in this case. Second, some of the X may belagged dependent variables but Durbin shows in JRSS(B), 1960 that LS holds asymptotically in this case. Third, $E(UU^1) \neq 6^2 I$ which implies that the error terms are serially correlated. In this case the best practical solution is to assume some relationship between the U's e.g. the autoregressive relationship. Fourth, some of the X may in face be interrelated which will tend to increase the size and standard errors of the regression coefficients.

In our analysis it is likely a priori that we will ~~sugger~~ suffer from the problems of intercorrelation between the X's because we include more than one lagged research expenditure variable in some equations and serial correlation in the residuals. Also the number of degrees of freedom available to obtain reasonable parameter estimates for the β is insufficient in this analysis to merit any final conclusions about the generality of the relationships expressed in equations 1 through 6.

We turn now to a presentation and discussion of the estimated equations.

5.3. Presentation of the Estimates

We first present the estimates on each of the equation forms 1 through 6 for both firms A and B.

5.3.1. I Equation forms 1, 2, 3 and 4 - Linear and Log-Linear Equations of R & D to Economic Results

Firm A (Note * denotes that a parameter is significant at the 5% level)

206

FIRM A

I. RELATION BETWEEN SALES AND RESEARCH AND DEVELOPMENT EXPENDITURES

1) $S_t = 1325400 + 19.140\, R_t$ D.F = 5

(922740) (4.3642)

$t = \underline{4.39}*$

$R^2 = 0.7937$
$R = 0.8909$
$F = 19.234$
$P = 0.007117$

2) $S_t = 2730700 + 17.127\, R_{t-1}$ D.F = 4

(918620) (4.884)

$t = \underline{3.51}*$

$R^2 = 0.7546$
$R = 0.8687$
$F = 12.297$
$P = 0.024745$

3) $S_t = 4016600 + 17.477\, R_{t-2}$ D.F = 3

(703750) (4.8208)

$t = \underline{3.63}*$

$R^2 = 0.8142$
$R = 0.9023$
$F = 13.143$
$P = 0.03611$

4) $S_t = 5191700 + 20.996\, R_{t-3}$ D.F = 2

(900550) (10.386)

$t = \underline{2.02}$

$R^2 = 0.6714$
$R = 0.8194$
$F = 4.0868$
$P = 0.1806$

5) $S_t = 3.941100 + 5.1197\, R_t - 11.914\, R_{t-1} + 26.269\, R_{t-2}$

(2156400) (19.754) (31.1933) (26.418)

$t = \underline{0.26}$ $t = \underline{0.37}$ $t = (\underline{0.99})$

D.F = 1

$R_2 = 0.9149$
$R^2 = 0.837$
$F = 1.7116$
$P = 0.49973$

6) $S_t = 4317200 - 5.7386\, R_{t-1} + 23.774\, R_{t-2}$

(1165100) (15.528) (17.97)

$t = \underline{0.37}$ $t = \underline{1.32}$

D.F = 2

$R_2 = 0.9089$
$R^2 = 0.8260$
$F = 4.7486$
$P = 0.17396$

7) $S_t = 4,389,700 + 4.8722\, R_{t-2} - 6.2626\, R_{t-3}$

(330450) (1.0884) (1.8953)

t = 4.48 t = 3.30

D.F = 1

$R = 0.9922$
$R^2 = 98.44\%$
$F = 3.1514$
$P = 0.12497$

1') $\log S_t = 1325400 + 19.140 \log R_t$ D.F = 5

(922740) (4.6342)

t = 4.39*

$R = 0.9739$
$R^2 = 0.9485$
$F = 92.01$
$P = 0.00020862$

2') $\log S_t = 10.5 + 0.42636 \log R_{t-1}$ D.F = 4

(0.7159) (0.06211)

t= 6.81*

$R = 0.9595$
$R^2 = 0.9206$
$F = 46.37$
$P = 0.00243$

3') $\log S_t = 12.626 + 0.26339 \log R_{t-2}$ D.F = 3

(C.64498) (0.057764)

t = 4.56*

$R = 0.9348$
$R^2 = 0.8739$
$F = 20.791$
$P = 0.019776$

4') $\log S_t = 14.643 + 0.097996 \log R_{t-3}$ D.F = 2

(1.0472) (0.096983)

t= 1.01

$R = 0.5814$
$R^2 = 0.3380$
$F = 1.0210$
$P = 0.41865$

5') $\log S_t = 18.897 - 0.54549 \log R_t - 0.44371 \log R_{t-1} + 0.7719 \log R_{t-2}$

(1.2281) (0.16290) (0.17137) (0.10637)

t = 3.35 t = 2.59 t = 7.26

D.F = 2

$R = 0.9978$
$R^2 = 0.9956$
$F = 75.906$
$P = 0.084129$

6') $\log S_t = 15.778 - 0.65141 \log R_{t-1} - 0.673.7 \log R_{t-2}$ D.F = 2

(1.9781) (0.39476) (0.25257)

t= 1.65 t= 2.67

$R = 0.9729$
$R^2 = 0.9466$
$F = 17.727$
$P = 0.053398$

7') $\log S_t = 10.229 + 0.93534 \log R_{t-2} - 0.50137 \log R_{t-3}$ D.F = 1

(0.68695) (0.13813) (0.090754)

t= 6.77 t= 5.52

$R = 0.9929$
$R^2 = 0.9859$
$F = 34.884$
$P = 0.11887$

8) $S_t = 1810200 + 46.234 M_t$ D.F = 5

(1144200) (14.99)

t= 3.08*

$R = 0.8096$
$R^2 = 0.6555$
$F = 9.5128$
$P = 0.027337$

8') $\log S_t = 8.292 + 0.63431 \log M_t$ D.F = 5

(3.7369) (0.34789)

t= 1.82

$R = 0.6319$
$R^2 = 0.3994$
$F = 3.3244$
$P = 0.12787$

9) $S_t = 1396800 + 47.951 C_t$ D.F = 5

(1023000) (12.421)

t= 3.86*

$R = 0.8653$
$R^2 = 0.7488$
$F = 14.904$
$P = 0.011873$

10') $\log S_t = 7.8828 + 0.67554 \log C_t$ D.F = 5

(1.0532) (0.098202)

t= 6.88*

$R = 0.9510$
$R^2 = 0.9044$
$F = 47.321$
$P = 0.00099320$

11) $S_t = 1191900 + 61.380\,R_t + 27.836\,M_t - 131.34\,C_t$ D.F = 3

(890200) (35.68) (20.116) (97.953)

t= 1.72 t= 1.38 t= 1.34

$R = 0.9428$
$R^2 = 0.8899$
$F = 8.0041$
$P = 0.06096$

11') $\log S_t = 7.3795 + 1.4543 \log R_t + 0.024710 \log M_t - 0.8779 \log C_t$

(1.0965) (0.6127) (0.12981) (0.6402)

t= 2.37 t= 0.19

D.F = 3

$R = 0.9848$
$R^2 = 0.9699$
$F = 32.196$
$P = 0.0087953$

12) $S_t = 2576700 + 7.8484\,R_{t-1} + 23.625\,M_t$ D.F = 3

(1014600) (14.732) (35.043)

t= 0.53 t= 0.67

$R = 0.887$
$R^2 = 0.7869$
$F = 5.5374$
$P = 0.098405$

12') $\log S_t = 10.825 + 0.5011 \log R_{t-1} - 0.1094 \log M_t$ D.F = 3

(1.3586) (0.2600) (0.3659)

t= 1.93 t= 0.30

$R = 0.9607$
$R^2 = 0.9229$
$F = 17.95$
$P = 0.021413$

13) $S_t = 3084000 + 22.157\,R_{t-1} - 14.119\,C_t$ D.F = 3

(1630200) (18.645) (49.948)

t= 1.19 t= 0.28

$R = 0.8723$
$R^2 = 0.7609$
$F = 4.7743$
$P = 0.11689$

13') $\log S_t = 13.19 + 0.69917 \log R_{t-1} - 0.52374 \log C_t$ D.F = 3

(1.95) (0.1949) (0.3588)

t= 3.59* t= 1.46

$R = 0.9765$
$R^2 = 0.9536$
$F = 300806$
$P = 0.01000$

14) $$S_t = \underset{(2077000)}{6839500} + \underset{\substack{(36.51)\\ t=\ \underline{1.92}}}{70.095\,R_{t-2}} - \underset{\substack{(67.21)\\ t=\ \underline{1.38}}}{92.731\,M_t} - \underset{\substack{(21.84)\\ t=\ \underline{0.89}}}{19.47\,C_t} \qquad D.F = \underline{1}$$

$R_2 = 0.9701$
$R^2 = 0.9411$
$F = 5.3282$
$P = 0.30589$

14') $$\log S_t = \underset{(0.89785)}{16.291} + \underset{\substack{(0.058268)\\ t=\ \underline{8.27*}}}{0.48173 \log R_{t-2}} + \underset{\substack{(0.10579)\\ t=\underline{0.56}}}{0.058753 \log M_t} \qquad D.F = \underline{1}$$

$$- \underset{\substack{(0.14855)\\ t=\ \underline{4.03}}}{0.59815 \log C_t}$$

$R_2 = 0.9969$
$R^2 = 0.9938$
$F = 0.5381$
$P = 0.088900$

15) $$S_t = \underset{(1387700)}{5526500} + \underset{\substack{(30.286)\\ t=\ \underline{1.80}}}{54.371\,R_{t-2}} - \underset{\substack{(60.771)\\ t=\ \underline{1.23}}}{74.843\,M_t} \qquad D.F = \underline{2}$$

$R_2 = 0.9457$
$R^2 = 0.8943$
$F = 8.4619$
$P = 0.10569$

15') $$\log S_t = \underset{(1.7826)}{13.63} + \underset{\substack{(0.13360)\\ t=\ \underline{2.51}}}{0.33538 \log R_{t-2}} - \underset{\substack{(0.26486)\\ t=\ \underline{0.62}}}{0.16326 \log M_t} \qquad D.F = \underline{2}$$

$R_2 = 0.9455$
$R^2 = 0.894$
$F = 8.4368$
$P = 0.10597$

16) $$S_t = \underset{(1480300)}{4528900} + \underset{\substack{(10.555)\\ t=\ \underline{2.01}}}{21.194\,R_{t-2}} - \underset{\substack{(25.115)\\ t=\ \underline{0.42}}}{10.479\,C_t} \qquad D.F = \underline{2}$$

$R_2 = 0.9105$
$R^2 = 0.8209$
$F = 4.8495$
$P = 0.17095$

16') $$\log S_t = \underset{(0.71864)}{16.363} + \underset{\substack{(0.04533)\\ t=\ \underline{10.76*}}}{0.49008 \log R_{t-2}} - \underset{\substack{(0.10253)\\ t=\ \underline{5.41*}}}{0.55515 \log C_t} \qquad D.F = \underline{2}$$

$R_2 = 0.9960$
$R^2 = 0.9919$
$F = 123.14$
$P = 0.0080555$

II Relationships net profits and research and development expenditures

17) $P_t = 104940 + 3.5742\, R_t$ d.f = 5

$(310650) \quad (1.4692)$

$t = \underline{2.43}$

$R = 0.7362$
$R^2 = 0.5420$
$F = 5.9178$
$P = 0.059187$

17') $\log P_t = 4.6163 + 0.73306 \log R_t$ d.f = 5

$(1.5956) \quad (0.13733)$

$t = \underline{5.34}$*

$R = 0.9223$
$R^2 = 0.8507$
$F = 28.493$
$P = 0.003947$

18) $P_t = 703540 - 1.5778\, R_t - 32.95\, R_{t-1} + 10.374\, R_{t-2}$ d.f = 1

$(50879) \quad (4.6609) \quad (7.5342) \quad (6.233)$

$t = \underline{0.34} \quad t = \underline{0.34} \quad t = \underline{1.66}$

$R = 0.9540$
$R^2 = 0.9100$
$F = 3.3718$
$P = 0.37609$

18') $\log P_t = 25.243 - 0.18316 \log R_t - 0.59545 \log R_{t-1} + 1.5996 \log R_{t-2}$

$(0.54603) \quad (0.072426) \quad (0.076191) \quad (0.04729)$

$t = \underline{25.29}$* $\quad t = \underline{7.82} \quad t = \underline{33.82}$*

d.f = 1

$R = 0.9999$
$R^2 = 0.9997$
$F = 1328.4$
$P = -0.020166$

19) $P_t = 233720 + 4.0121\, R_{t-1}$ d.f = 4

$(278840) \quad (1.4825)$

$t = \underline{2.71}$

$R = 0.8042$
$R^2 = 0.6468$
$F = 7.3241$
$P = 0.053742$

20) $\log P_t = 7.9969 + 0.47408 \log R_{t-1}$ D.F = 4

$(1.7149) \quad (0.14997)$

$t = \underline{3.16}$*

$R = 0.8451$
$R^2 = 0.7141$
$F = 9.992$
$P = 0.03415$

21) $$P_t = \underset{(228430)}{319220} + \underset{(1.5648)}{5.5223}\, R_{t-2}$$ d.f = 3

t= 3.53*

$R = 0.8977$
$R^2 = 0.8059$
$F = 12.455$
$P = 0.038664$

22) $$\log P_t = \underset{(1.665)}{8.515} + \underset{(0.1491)}{0.4547} \log R_{t-2}$$ d.f = 3

t= 3.05*

$R = 0.8696$
$R^2 = 0.7562$
$F = 9.3040$
$P = 0.055417$

23) $$P_t = \underset{(423940)}{526700} + \underset{(4.8894)}{8.0876}\, R_{t-3}$$ d.f = 2

t= 1.65

$R = 0.7601$
$R^2 = 0.5777$
$F = 2.736$
$P = 0.23993$

24) $$\log P_t = \underset{(2.7902)}{11.1962} + \underset{(0.25841)}{0.17177} \log R_{t-3}$$ d.f = 2

t= 0.66

$R = 0.4254$
$R^2 = 0.1810$
$F = 0.4418$
$P = 0.57462$

3.2. II Equation forms 1 & 2 & 3 & 4 - LINEAR AND LOG LINEAR EQUATIONS OF R & D TO ECONOMIC RESULTS

FIRM B

I RELATIONSHIPS BETWEEN R & D EXPENDITURES AND SALES

1) $$S_t = \underset{(87284)}{1196100} - \underset{(1.6552)}{11.077}\, R_t \qquad \text{d.f} = \underline{4}$$

t= 6.67*

$R = 0.9581$
$R^2 = 0.9180$
$F = 44.784$
$P = 0.0025934$

1') $$\log S_t = \underset{(1.4338)}{23.831} - \underset{(0.13366)}{0.98054} \log R_t \qquad \text{d.f} = \underline{4}$$

t= 7.34*

$R = 0.9648$
$R^2 = 0.9208$
$F = 53.821$
$P = 0.0018377$

2) $$S_t = \underset{(60466)}{1249600} - \underset{(1.0682)}{9.8299}\, R_{t-1} \qquad \text{d.f} = \underline{3}$$

t= 9.20*

$R = 0.9827$
$R^2 = 0.9658$
$F = 84.68$
$P = 0.0027142$

2') $$\log S_t = \underset{(1.1136)}{22.612} - \underset{(0.1027)}{0.8452} \log R_{t-1} \qquad \text{d.f} = \underline{3}$$

t= 8.23*

$R = 0.9785$
$R^2 = 0.9576$
$F = 67.68$
$P = -0.0037595$

3) $$S_t = \underset{(107000)}{1193600} - \underset{(1.7478)}{6.7168}\, R_{t-2} \qquad \text{d.f} = \underline{2}$$

t= 3.84

$R = 0.9385$
$R^2 = 0.8807$
$F = 14.769$
$P = 0.061527$

3') $$\log S_t = \underset{(0.9737)}{19.796} - \underset{(0.088912)}{0.56789} \log R_{t-2} \qquad \text{d.f} = \underline{2}$$

t= 6.39*

$R = 0.9764$
$R^2 = 0.9533$
$F = 40.795$
$P = 0.023647$

4) $$S_t = \underset{(53178)}{1187100} - \underset{(0.80409)}{5.2297}\, R_{t-3} \qquad \text{d.f} = \underline{1}$$

t= 6.50

$R = 0.9884$
$R^2 = 0.9769$
$F = 42.30$
$P = 0.09712$

215

4') $$\log S_t = 18.308 - 0.42194 \log R_{t-3}$$ d.f. = 1

(0.27328) (0.024750)

$t = \underline{17.05}$*

$R = 0.9983$
$R^2 = 0.9966$
$F = 290.64$
$P = 0.037300$

6) $$S_t = 133590 - 9.2994\, R_{t-1} - 1.9698\, R_{t-2}$$ d.f = 1

(120560) (5.8566) (3.2669)

$t = \underline{1.59}$ $t = \underline{0.6}$

$R = 0.9829$
$R^2 = 0.9661$
$F = 14.262$
$P = 0.18404$

6') $$\log S_t = 20.454 - 0.25677 \log R_{t-1} - 0.37706 \log R_{t-2}$$ d.f = 1

(1.198) (0.26435) (0.2168)

$t = \underline{0.97}$ $t = \underline{1.74}$

$R = 0.9879$
$R^2 = 0.976$
$F = 20.293$
$P = 0.15507$

9) $$S_t = -5987 + 15.101\, C_t$$ d.f = 4

(61644) (1.3353)

$t = \underline{11.31}$*

$R = 0.9847$
$R^2 = 0.9697$
$F = 127.9$
$P = 0.000348$

10) $$\log S_t = 2.2061 + 1.0464 \log C_t$$ d.f = 4

(1.1209) (0.10548)

$t = \underline{9.92}$*

$R = 0.9803$
$R^2 = 0.9609$
$F = 98.40$
$P = 0.000579$

13) $$S_t = 621460 - 4.6739\, R_{t-1} + 7.3854\, C_t$$ d.f = 2

(625600) (5.2211) (7.3214)

$t = \underline{0.9}$ $t = \underline{1.01}$

$R = 0.9886$
$R^2 = 0.9773$
$F = 43.1$
$P = 0.022678$

13') $$\log S_t = 10.295 - 0.29595 \log R_{t-1} + 0.59344 \log C_t$$ d.f = 2

(6.666) (0.30469) (0.31873)

$t = \underline{0.97}$ $t = \underline{1.96}$

$R = 0.9922$
$R^2 = 0.9845$
$F = 63.398$
$P = 0.3043$

16) $S_t = 159920 - 0.42011\, R_{t-2} + 12.509\, C_t$ d.f = 1

(1932000) (11.941) (23.32)

t= 0.04 t= 0.54

$R = 0.9526$
$R^2 = 0.9079$
$F = 4.89$
$P = 0.3043$

16') $\log S_t = 34.611 - 1.1027 \log R_{t-2} - 0.82479 \log C_t$ d.f = 1

(21.371) (0.77726) (1.1881)

t= 1.42 t= 0.69

$R = 0.9841$
$R^2 = 0.9685$
$F = 15.355$
$P = 0.17758$

II Relationships between net profits and research and development expenditures

17) $P_t = 141400 - 1.4329\, R_t$ d.f = 4

(31141) (0.59056)

t= 2.43

$R = 0.7716$
$R^2 = 0.5954$
$F = 5.8869$
$P = 0.072269$

17') $\log P_t = 24.254 - 1.2336 \log R_t$ d.f = 4

(4.258) (0.39691)

t= 3.11*

$R = 0.8409$
$R^2 = 0.7072$
$F = 9.6594$
$P = 0.035943$

19) $P_t = 126690 - 0.84418\, R_{t-1}$ d.f = 3

(48549) (0.85767)

t= 0.98

$R = 0.4941$
$R^2 = 0.2441$
$F = 0.96879$
$P = 0.39756$

20) $\log P_t = 17.186 - 0.54789 \log R_{t-1}$ d.f = 3

(5.0393) (0.46494)

t= 1.18

$R = 0.5625$
$R^2 = 0.3164$
$F = 1.3887$
$P = 0.32359$

21) $P_t = 141590 - 0.9755\, R_{t-2}$ d.f = 2
$(79507) \quad (1.2987)$
$t = \underline{0.75}$

$R = 0.4691$
$R^2 = 0.2200$
$F = 0.56417$
$P = 0.53094$

22) $\log P_t = 18.425 - 0.65346 \log R_{t-2}$ d.f = 2
$(9.1695) \quad (0.83730)$
$t = \underline{0.78}$

$R = 0.4832$
$R^2 = 0.2334$
$F = 0.60908$
$P = 0.51684$

23) $P_t = 184960 - 1.4897\, R_{t-3}$ d.f = 1
$(123830) \quad (1.8723)$
$t = \underline{0.8}$

$R = 0.6226$
$R^2 = 0.3876$
$F = 0.63302$
$P = 0.57215$

24) $\log P_t = 22.883 - 1.0477 \log R_{t-3}$ d.f = 1
$(14.103) \quad (1.2772)$
$t = \underline{0.82}$

$R = 0.6342$
$R^2 = 0.4023$
$F = 0.67296$
$P = 0.56263$

5.3.3 Equation forms 5 & 6 Input output relation ships

Firm A - I Relationships between sales and R & D inputs

1) $\log S_t = 21.166 - 4.859 \log C_t + 5.128 \log K_t - 0.269t$
$(2.149) \quad (0.874) \quad (0.827) \quad (0.082)$
$t = \underline{5.56}^* \quad t = \underline{6.20}^* \quad t = \underline{3.26}^*$

d.f = 3
$R = 0.9969$
$R^2 = 99.38\%$ explained
$F = 160.9$
$P = 0.0008$

218

2) $\log S_t = 18.09 - 2.931\log C_t + 3.09 \log K_t$ d.f = 4

$\quad (3.56) \quad (1.19) \quad (1.00)$

$\quad t = \underline{2.47} \quad t = \underline{3.09}^*$

R_2 = 0.9859
R^2 = 97.20% explained
F = 69.36
P = 0.0008

II RELATION BETWEEN SALES AND TOTAL FIRM RESOURCE INPUTS

m A

1) $\log S_t = 4.986 + 0.737 \log F_t + 0.022 \log L_t + 0.258\, t$

$\quad (15.483) \quad (1.34) \quad (0.566) \quad (0.641)$

$\quad t = \underline{0.55} \quad t = \underline{0.04} \quad t = \underline{0.40}$

d.f = 1

R_2 = 0.9701
R^2 = 94.12% explained
F = 5.33
P = 0.306

2) $\log S_t = -0.711 + 1.145 \log F_t + 0.164 \log L_t$ d.f = 2

$\quad (4.765) \quad (0.668) \quad (0.337)$

$\quad t = \underline{1.72} \quad t = \underline{0.49}$

R_2 = 0.9652
R^2 = 93.17% explained
F = 13.63
P = 0.068

m B

1) $\log S_t = 11.06 + 0.099 \log F_t + 0.064 \log L_t + 0.186\, t$

$\quad (9.54) \quad (0.892) \quad (0.133) \quad (0.202)$

$\quad t = \underline{0.11} \quad t = \underline{0.48} \quad t = \underline{0.92}$

d.f = 1

R_2 = 0.9715
R^2 = 94.37% explained
F = 5.59
P = 0.299

2) $\log S_t = 2.804 + 0.892 \log F_t - 0.018 \log L_t$ d.f = 2

$\quad (3.14) \quad (0.227) \quad (0.095)$

$\quad t = \underline{3.93} \quad t = \underline{0.19}$

R_2 = 0.9466
R^2 = 89.60%
F = 8.61
P = 0.104

5.4. Discussion of the Estimates

(Note: - the units in the equation are money values)

Our purpose is to determine whether reasonable relationships seem to exist between economic results and R & D expenditures even though the "small sample" problem reduces the value of the analysis. It seems for firm A that the most useful relationships are the following:

I Equations of forms 1 and 3 (i. e. $S_{ti} = f(R_{(t-\alpha)i})$ or $\log S_{ti} = f(R_{(t-\alpha), i})$

(i) Equation 3) shows that $S_t = f(R_{t-2})$ is the best fitting single variable relationship. This confirms the view that for this firm there is approximately a two year lag between present R & D expenditures and future economic results of the firm. However, we should note that the number of degrees of freedom was very small and that in equations 1) and 2) there was a good fit between sales and present R & D expenditures and also between sales and R & D expenditures lagged one year.

(ii) If we view the log linear forms of the equations discussed in (i) we find that the equations with lags of 0, 1 and 2 years have significant regression coefficients and good fits. This would suggest that the equation form linking sales to research and development expenditures with lags of zero, one and two years simultaneously might be the most suitable.

(iii) Whilst relationships such as 7) or 5)[1] which are of the form suggested seem promising, none of the individual regression coefficients is significant under a t test though the fit measured by R^2 is good. 5)[1] seems to be the most promising because the F test which is a joint test for all the estimated regression coefficients together (or if it is simpler, think of it as a test of the multiple correlation coefficient) is highly significant in this case. However, we must remember that the fit (or the value of R^2) tends to be improved because of the intercorrelation between R_t, R_{t-1}, and R_{t-2}.

It seems reasonable to conclude that with larger samples of data for firm A we would tend to get confirmation of the strong relationships between R & D and sales suggested by the present study. If this is the case then we have the framework of a method for predicting the level of R & D expenditures provided we are able to make a reasonable forecast for the growth in turnover or sales. Such a forecast could be made by a number of methods which we shall take up in the concluding part of this chapter which assesses the relevance of the results.

II Equations of forms 2 and 4

Equations 8) and 9) relating net sales to marketing expence and technical capability respectively give significant values for the simple regression coefficients but the unexplained residual variance in net sales is fairly large suggesting that the independent influence of M_t and C_t on net sales is insufficient for explaining variations in net sales. Clearly M_t and C_t have some effect on net sales but it is equally apparent from a study of the other estimated relationships that their joint inclusion with R & D variables gives a much better explanation of the variation in net sales. This confirms a priori reasoning but because of the limited number of degrees of freedom available we cannot estimate many variable relationships efficiently or accurately.

III Equations relating R & D expenditures to net profits

Again equations 17^1), 20), 21) and 22) show that there is either a reasonable additive or multiplicative relationship between net profits and R & D expenditures. Further the joint effect of lags of 0, 1 and 2 years on net profits expressed in equation 18^1) is seen to be very strong. This strengthens the hypotheses that R & D expenditures have cumulative and not necessary immediate effects on the economic results of the firm but again this finding must be tentative because of the small samples of data available and possible intercorrelations between the lagged research and development variables.

For Firm B a similar picture tends to emerge but the influence of lagged R & D expenditures differs slightly reflecting the firm's strategy of undertaking a large number of small cost R & D projects which tend to have more immediate impact on economic results than if the project were more technically complex. However, we shall consider the estimated equations for B in the same manner as for A so that subsequent comparison can be facilitated.

Firm B

I Equations of Forms 1 and 3

Equations 1), 1^1), 2), and 2^1) show that variations in net sales in B are explained most satisfactorily by present R & D expenditures and those one year ago. This finding reflects and confirms a priori knowledge of the relatively large number of small cost and thus quickly resolved research projects in the firm. Research output thus has a greater immediate impact on sales in B. We can again, therefore, make use of these findings in determining R & D expenditures provided that we can make realistic forecasts of global sales.

II Equations of Forms 2 and 4

The most interesting equations here are numbers 9) and 10) which show strong, good fitting relationships between sales and the technical capability of the firm. This finding confirms our initial hypotheses that technical capability influences economic results.

III Equations Relating R & D Expenditures to Net Profits

The fit of the relationships here is generally poor, 17^1 showing some evidence for a viable log-linear relation between profit and R & D expenditures. The result is not altogether surprising given the research strategy of the managing director in

Firm B and the rather piecemeal treatment of R & D in the firm. R & D does not seem a priori to fulfill profit objectives in the firm and is undertaken without regard to financing firm growth out of R & D. Thus one would not tend to expect a dynamic effect of R & D on net sales in B.

We should briefly consider the results of the input output analyses. These show that for both firms A and B the relationship between net sales and the total factors of production mix in the firm was a weak one. Only in the case of Firm A for the R & D department alone, see equations 1) and 2), was the relation between net sales and the factors of production mix useful. Equations 1) and 2) show that the elasticities of sales with respect to R & D labour and capital are numerically greater than one and are negative and positive respectively. The signs of the elasticity coefficients imply that reductions in R & D labour costs and increases in technical capital costs will tend to increase the level of net sales in the firm. This in turn suggests decreasing returns to R & D labour and increasing returns to R & D equipment. The negative sign of the growth or trend term is reasonable in view of the rapid nature of technical change in the industry and consequently rapid time obsolescence of products.

5.5. Summary of Results across both Firms A and B

Despite the limited scope of the analysis it is reasonable to conclude that:

a) R & D expenditures influence economic results in both firms A and B. The difference in the lag structures for the R & D expenditures in each case can be explained by the nature of the R & D activity in each firm. A has a small number of high cost relatively technically advanced projects and with such projects the research pay off takes longer than in B's case where a large number of smaller projects of a more immediate value to the firm are undertaken.

b) Technical capability also influences R & D results, the relationship being slightly stronger for B.

c) The relation between R & D expenditures and profitability is most apparent and useful in Firm A. This finding confirms the evidence on A's profit and growth orientation highlighted in the initial questionnaire study. Firm B's R & D expenditures have a much weaker bearing on profitability and this again confirms the results of the questionnaire study on the lack of formal awareness of objectives for R & D in firm B.

d) The 'input-output' analyses show little and the only strong findings refer to firm A.

In general the results must be viewed very cautiously and must await amplification from the author's continuing studies in this field. However, it is reasonable to draw some tentative implications for the R & D budgeting process. With the small sample evidence it is reasonable to expect that the fit of a linear relationship will be good but we have no real evidence on the nature of the relationship.

5.6. Implications of the Results

It is clear that some form of relationship exists between research and development expenditures and sales and that with a larger sample of data we could establish the exact nature of the relationship and thus fit the derived functional form accurately by means of efficient methods of statistical estimation such as least squares, minimising absolute deviations or maximum likelihood.

Given that it should be practically possible to find a relationship NET SALES = f (R & D EXPENDITURES) we can try to predict the level at which R & D expenditure should be set. This is achieved by using corporate targets for the growth of net sales for the firm as a whole to give us a value for the dependent variable net sales in the present period from which the values of the independent variables for the same period could be calculated by using the estimated relation between net sales and R & D expenditures (with or without a lag structure).

In essence we are saying that we should try a number of alternative targets for the growth in sales for the firm next year and for each calculate the implied level of R & D expenditures. This analysis would enable the upper and lower bound for the R & D budget to be established. Formally, the approach is first to find $S_{t+1} = S_t(1+r)$, where S_t is net sales in t th period, S_{t+1} is estimated net sales for the (t+1) th period and r is the growth rate in sales. Second, given S_{t+1} use the estimated functional form between net sales and R & D expenditures with stable parameters for the present period to estimate the implied level of R & D expenditures in period (t+1).

It should be noted that the first part of the approach requires the estimation of possible growth rates, r, in sales. We could in practice estimate r in terms of a series of probabilistic forecasts and thus weight the estimated values for R & D expenditures by the weightings of the probabilities of occurrence of various values of r. Alternatively, the forecast for S_{t+1} could be obtained directly by either fitting a mathematical trend curve [6] to the past data on sales and extrapolating the curve onto future periods or considering the use of exponential smoothing or weighted moving average techniques[7].

This approach of finding R & D expenditures by evaluating their effect on economic results to set appropriate levels for R & D is throught to be much more useful at the level of the individual firm than any of the approaches outlined by Hart or Duckworth. This

6. See ICI MONOGRAPH "Mathematical Trend Curves" Oliver and Boyd
7. See ICI MONOGRAPH "Short Term Forecasting" Oliver and Boyd

approach owes a great deal to Mansfield's work but differs in that the level of R & D is determined from estimates of global targets for sales etc. within the firm. Mansfield considers in his model an R & D budget determined as a function of the firm's size and the expected rates of return from R & D projects. Thus Mansfield builds up from the individual project to the budget. Thus the method outlined here neglects individual projects and assumes that the firm wishes to grow year by year by a targeted amount (vide Firm A) and that from this growth figure the amount that should be spent on R & D can be determined.

5.7. Summary and Conclusions

The analysis reflects the difficulties that are inherent in econometric work at the micro-level. For various reasons of sample size and associated estimation problems little reliance can be placed on the specification and the resultant estimation of the various relationships. Yet it is clear that the simple invention - innovation model for the R & D process is useful and that relationships derived in this way can be used to establish limits within which R & D expenditures can be set.

In the longer term with a greater sample size from each of the firms and with the addition of other firms in the same technology to the sample, the estimated relationships at the micro-level can be placed on a sounder statistical foundation.

PART III

RETROSPECTIVE R & D PROJECT ANALYSIS

Introduction

Professor B. R. Williams[1] in his commentary on the FBI survey emphasises the apparent lack of awareness and interest in firms in research economics and the high wastage rates in R & D in some industries. Admittedly, this survey is now some years out of date but the findings raise questions about the efficiency and effectiveness of research and development undertaken at the firm level. In particular, how efficient is R & D in the firm? Does effectiveness depend upon the type of organisation and the type of product?

Therefore, the problem we tackle here is the evaluation of R & D at the firm level. To do this we carry out a retrospective cost/benefit analysis of past R & D project programmes and allocations in two firms, A and B, in the electronics industry.

This part of the thesis begins with a literature review of relevant cost/benefit studies and continues with an analysis of the effectiveness of past R & D work. This is followed by a short econometric analysis of some of the data to find out whether past information in R & D performance can be helpful in improving the future effectiveness of R & D in the firm.

---

1. B. R. Williams, "Commentary on Behalf of the NIESR", FBI Survey on R & D in Manufacturing Industry, 1961. p. 27.

Chapter 6

Literature Survey on the Cost Benefit Analysis of Research and Development Work

6.0. Introduction

Peck in a recent paper[1] comments that it is said that British managers reach research and development project decisions that make inadequate allowance for marketability, cost and production considerations. Execution of projects is said to lack the sense of urgency necessary for timely completion. This comment ties in with his thesis that Britain is over-committed in research and development and thus does not make proper economic use of expenditures.

This chapter reviews the literature on the cost-benefit analysis of research and development work and summarises the present evidence about the effectiveness of research and development work.

6.1. Literature Survey

Baker and Pound[2] in their review of formal selection models found few references which gave data and discussed the role of uncertainty in research and development project selection.

The RAND Corporation economists Marshall and Meckling[3] however, carried out one of the pioneer analyses of estimate accuracy

1. M. J. Peck, "Science and Technology", in Britain's Economic Prospects (ed) R. E. Caves, Allen and Unwin, 1968. p. 448.
2. N. R. Baker and W. H. Pound, "R & D Project Selection: Where We Stand", I. E. E. E. Transactions on Engineering Management Vol. Em-11, No. 4 (December 1964).
3. A. W. Marshall and W. H. Meckling, "Predictability of Costs, Time and Success of Development" in R. R. Nelson (ed) "The Rate and Direction of Inventive Activity" Princeton (1962).

and the role of uncertainty in research and development projects. Their analysis was carried out on government sponsored research and development in the fields of aerospace and military production.

The value of Marshall and Meckling's work is that they outline clearly the framework within which we should evaluate effectiveness of research and development programmes. They concentrate on the confidence or accuracy which can be attached to predictions made by research and development managers about the success of particular development projects. Success of a project is defined in terms of the difference between the value of the final output and the total costs of production. In order to measure success we have to estimate four factors which affect it, viz. Costs (development and production), Performance, Time of Availability, and Utility. Cost and Time of Availability are self explanatory, whilst Performance relates to the specification and working ability of the end product and Utility is a measurement of the value of the end product to the military authorities in terms of weapons systems available elsewhere. A major problem is, of course, that predictions of the various factors are rarely available in a systematic form, lack quantification and thus cannot be verified easily. In addition, the factors themselves are inter-related, e.g. to obtain a given level of performance, sufficient time and cost resources must be set aside. If the level is not attained with the specified cost/time allocation a decision must be made to allocate extra time or cost or both. Also, specifications of projects rarely stay the same either because of technical problems or knowledge of the success of a similar project in some other country.

In the evaluation of the predictive accuracy of initial cost estimates there are a number of difficulties. The costs finally incurred on a given project relate to the costs of actual production and the performance configurations eventually adopted. Initial estimates of cost reflect the initial designs and specification for the project which, because of the dynamic nature of technical knowledge, do not generally remain the same during the life of the project. For this reason alone it would not be surprising for initial and final estimates of cost to differ quite considerably. However, measurement of the extent of the difference between estimated and actual cost depends upon our definition of cost. Marshall and Meckling convincingly argue that if we treat cost estimates, however they are generated, as if they were estimates of achieving the expected levels of performance by a given date, we can measure the uncertainty in the cost factor in our decision by observing changes in the cost estimates. They further suggest that the error in cost estimates can reasonably be divided into two parts: first, due to intrinsic cost estimation error with a given specification and second, due to specification change as development proceeds. If this division is correct it implies that major improvements in initial forecasting should occur through early prediction of the final design and specification.

Marshall and Meckling thus analyse the prediction error by dividing the latest possible production cost estimat e by the earliest possible estimate. The factors obtained are presented in Tables I and II in unadjusted form and with adjustments for changes in price levels and final output (because most early estimates are made on the basis of producing an estimated expected output which in general differs from the actual output). It is clear from both sets of factors that initial cost estimates have over-optimistic biases, in fact, on average the most recent estimates exceeded the earliest available estimates by between and three times.

Table 1

TOTAL FACTOR INCREASES IN AVERAGE CUMULATIVE COST OF PRODUCTION - UNADJUSTED

Fighters	Factor	Bombers	Factor	Cargoes & Tankers	Factor	Missiles	Factor
1	5.6	1	8.7	1	1.7	1	57.6
2	3.6	2	3.5	2	1.6	2	20.7
3	3.1	3	1.5	3	1.0	3	11.1
4	2.1			4	1.0	4	10.3
5	1.9					5	1.5
6	1.5					6	1.3
7	1.4						
8	1.2						
9	1.2						
Mean	2.4		4.5		1.3		17.1(9.0+)

Mean - All classes 6.5 (4.+)

\+ excluding missile case No. 1

Source Marshall and Meckling (op cit.) p. 11 (RAND Corporation, P. 1821-1959)

Table II

TOTAL FACTOR INCREASES IN AVERAGE CUMULATIVE COST
OF PRODUCTION - ADJUSTED

Fighters	Factors A	Factors B	Bombers	Factors A	Factors B	Cargoes & Tankers	Factors A	Factors B	Missiles	Factors A	Factors B
1	3.9	4.0	1	6.2	4.0	1	1.4	1.6	1	14.7	6.4
2	2.6	2.5	2	2.8	2.8	2	1.5	1.5	2	9.4	6.0
3	2.0	2.0	3	1.1	1.2	3	1.0	0.9	3	4.4	2.7
4	1.5	1.5				4	1.0	0.8	4	7.2	7.1
5	1.7	2.1							5	1.5	1.3
6	1.2	1.2							6	1.1	0.8
7	1.0	0.8									
8	1.0	1.0									
9	1.1	0.6									
Means	1.8	1.7		3.4	2.7		1.2	1.2		6.4	4.1

Means - All Classes

A	B
3.2	2.4

Source Marshall and Meckling (op cit) p. 14 (RAND Corporation, P. 1821, 1959)

When looking at tables I and II it is interesting to discover whether estimates of cost are more accurate when projects have only a small degree of technical difficulty. Marshall and Meckling asked a number of technical experts to classify the twenty two development programs they analysed according to the technical advance sought in each - small, medium or large - and they then rearranged the entries in Table II by this small, medium and large classification to give table III shown immediately below.

Table III

COST FACTORS CLASSIFIED ACCORDING TO TECHNOLOGICAL ADVANCE

	SMALL		MEDIUM		LARGE	
	Factor A	Factor B	Factor A	Factor B	Factor A	Factor B
	1.5	1.5	2.8	2.8	1.1	1.2
	1.7	2.0	2.6	2.5	1.0	1.0
	1.0	0.8	2.0	2.0	1.0	0.8
	1.4	1.6	1.2	1.2	6.2	4.0
	1.0	0.9	1.1	0.6	1.1	0.8
	1.5	1.5	1.5	1.1	14.7	6.4
					3.9	4.0
					4.4	2.7
					7.2	7.0
					9.4	6.0
Means	1.3	1.4	1.8	1.7	5.0	3.4

Clearly, there is a strong correlation between the accuracy of cost forecasts and the degree of technological advance of a project i. e. the greater the advance, the more inaccurate the forecast.

Availability estimation errors measured by the time difference between early estimates of completion dates and actual completion dates generally show the same type of over-optimistic bias. The mean "slippage" betweenactual and estimated times is 2 years which is significantly large, but to assess the extent of the significance, i. e. to allow for different project lives, it is necessary to construct ratios of the actual time to completion to early predictions of completion time. On average projects take 50% more time than the earliest prediction would indicate.

Early performance estimates are much more often fulfilled than early cost and availability estimates in Marshall and Meckling's sample of projects. The reason is to be found in the nature of government sponsored development work. Centrally funded work has to fulfil performance objectives even if the trade off is time slippage in completion or increased cost of production and development. Even so, in most of the twenty-two cases performance goals were not fully achieved.

A further important question that Marshall and Meckling try to resolve is the behaviour of the estimates through time. At what time do estimates become reasonably accurate and thus usable for economic evaluation purposes? The general conclusion is that the accuracy of estimates is a function of the stage of development. This also means that estimates for development projects representing only limited technical advancement tend to be better than estimates for more ambitious projects.

Peck and Scherer[4] as part of an analysis of the weapons acquisition process calculate estimate errors for aerospace developments. Their findings of a threefold (average 3.2 times) over-optimistic bias in cost estimates and a time slippage bias of 36% more than the early time estimates are in close agreement with RAND studies. Both studies, however, were of government sponsored programmes and these tend to have different objectives from commercially oriented development work. Therefore, whilst we can tentatively say that military programmes show consistent over-optimistic biases in the estimation of economic, time, and to a lesser extent, performance factors, we cannot generalise these results to industrial research and development work.

However, before leacing military R & D studies we must mention the very recent paper by Summers[5] which extends the cost-effectiveness analysis approach by studying 68 historical Rand Corporation military R & D case studies including the evidence from Marshall and Meckling's study. The basic aim of Summer's work is to try to give an answer to the questions, how unreliable are cost estimates and in what directions are they unreliable? His analysis closely follows Marshall and Meck-

---

4. M. J. Peck and F. M Scherer, The Weapons Acquisition Process, Division of Research, Harvard, 1962
5. R. Summers, "Cost Estimates as Predictors of Actual Costs: A Statistical Study of Military Developments", in T. Marschak, T. K. Glennan and R. Summers, Strategy for R & D, Srpinger-Verlag, 1968, p. 140.

ling's in that he calculates raw and adjusted (for price changes and changes in expected output levels) ratios of actual cost to initial estimated cost. He finds that the initial estimates are far from accurate and that the bias in estimation of costs is largely on the side of the underestimation of costs. Specifically, four fifths of the initial estimates of cost are less than their actual values and one quarter of the estimates of cost are less than half of the total actual costs. In this respect, of course, the findings agree with the magnitude of bias found in the other military R & D studies. The difference here is that Summers tries to find the detailed micro reasons for the inaccuracy that exists in cost estimation for research projects.

He identifies several variables which seem to influence estimation performance. They are, first, the point in time during the development when the estimate is made; second, the level of technical difficulty offered by a project; third, the length of the development period i. e. the longer the development period the more likely it is that the initial design specification and configuration will be changed; fourth, the experience which estimators have previously had in assessing estimates for R & D projects. He then tries to assess the extent to which each of these variables can explain the observed variability in the ratio of the actual cost to the initial adjusted estimate. He finds that the character of the development program and the timing of the estimates are important in explaining the observed variability. This means simply that cost

Estimates are good for projects offering a small technical advance and vice-versa and that if early estimates of cost are poor then later ones will be better. Also he finds that inaccuracy is greater the longer the development period and that estimation performance is improved when comparing chronologically later projects with earlier ones. However, Summers considers that the most critical factor in determining the accuracy of a cost estimate seems to be the degree of uncertainty, at the time the estimate is made, about the exact design configuration of the product at the end of the development program. Having analysed the factors which seem to be the major explanatory reasons for inaccuracy, he attempts to show that we can adjust initial estimates by a factor to correct the estimate for the biases of inaccurate forecasting. Summers uses multiple regression methods to relate the ratio of actual cost to the initial cost estimate to the degree of technical difficulty and the point in time during the development period when the estimate is made. With this relationship he obtains a debiasing formula which he rejects as a means of adjusting initial cost estimates.

Table IV given below presents the results of Summer's basic analysis of ratios of final cost to initial cost values. We shall take up his more detailed analysis in the next chapter.

Table IV

SUMMERS COST-FACTOR FREQUENCY DISTRIBUTION

(1) Class Intervals Cost Factors	(2) Frequency of Unadjusted Cost Factors (Raw F)	(3) Frequency of Adjusted Cost Factors (F)
0.60 - 0.99	13	14
1.00 - 1.39	17	23
1.40 - 1.79	12	10
1.80 - 2.19	7	5
2.20 - 2.99	3	6
3.00 - 3.79	5	4
3.80 - 4.99	3	2
5.00 - 9.99	4	4
10.00 -19.99	2	-
20.00 -39.00	2	-
	68	68
Mean	3.26	1.79
Standard Deviation	5.39	1.34
Root-Mean-Square Error	5.85	1.56

Source R. Summers p. 152 in Strategy for R & D ed. by T. Marschak et al.

The reported evidence on the relation between estimated and actual outcomes of development work in an industrial context is much more sparse. Undoubtedly, the major reason for lack of research results is the blanket of company security over past research and development results.

Professor Mansfield in two recent studies [6, 7] has initiated the detailed study of the relation between estimated and actual outcomes in industrial research and development. Of about 45 projects he studied in an equipment laboratory only 50% resulted in commercial success though the accuracy of cost estimates was generally very good and only a small way out for projects that resulted in technical failure. We present the information on these 45 projects in Table V below:

Table V

MANSFIELD: RATIO OF ACTUAL EXPENDITURES TO FINAL BUDGET APPROVED BY LABORATORY MANAGEMENT, 45 R & D PROJECTS, 1963

Ratio	Number of Proposed Projects
0.00 - 0.39	2
0.40 - 0.79	21
0.80 - 1.19	16
1.20 - 1.59	3
1.60 and over	3
	45

Source E Mansfield and R.G. Brandenberg: Journal of Business, October 1966

6. E. Mansfield, Econometric Studies of Industrial Research and Technological Innovation, W.W. Norton, New York, 1968.
7. E. Mansfield and R. Brandenberg, "The Allocation, Characteristics, and Outcome of the firm's R & D Portfolio: A Case Study", Journal of Business October, 1966.

Further, about one half of the laboratory's projects did not achieve their technical objectives on time and this implies a fairly large area of technical uncertainty in research and development. However, Mansfield points out that the delay in two-thirds of the time slippage porjects could be explained either by changes in project objectives or by transfer of personnel to other projects. Therefore, in only one-sixth of all the projects was there a relatively large element of technical uncertainty, suggesting that time slippage errors overstate the problem of uncertainty in research and development.

Mansfield's major conclusions about industrial research and development differ from those of the military research and development studies. Cost estimates tend to be more accurate, expected profit seems to be the major objective in industrial research and development work and technical uncertainty seems to be smaller in industrial research and development because of its applied nature, even though time slippages occurred in half of the projects studied. Performance objectives seem to be met in the majority of cases in both military and industrial research and development. If Mansfield's analysis is correct it suggests that strategies for research and development work should differ between industrial and military research and development and that policies designed to reduce uncertainty in research and development will be more useful in those areas where uncertainty is greatest, viz. military research and develop ment.

Meadows[8] has also collected data on the accuracy of project estimates in industrial research and development and is engaged on further studies to determine the relationship between estimated and actual outcomes in commercial development projects. Meadows discusses the effect of inaccuracies in the estimation of such factors as probability of technical success (PTS), probability of commercial success (PCS), net profit (NP) if the project is successful, the development costs (DC), which are frequently used as inputs to indices purporting to measure project worth. An example of this type of measure is the expected profit ratio suggested by Meadows, viz.

$$\text{EXPECTED PROFIT RATIO} = \frac{(PTS) \times (PCS) \times (NP)}{DC}$$

It can easily be seen that estimation errors in any of the factors in the numerator and denominator of this ratio may distort the measure of project worth and throw considerable doubt on a decision to go on a project based solely on expected profit index.

Meadow's data sources comprise three chemical laboratories, one electronics laboratory and the information from the equipment laboratory collected by Mansfield. We present the evidence Meadows has collected about cost factor ratios on Table VI overleaf:

---

8. D. Meadows, "Estimate Accuracy and Project Selection Models in Industrial Research", p. 105-121, <u>Industrial Management Review,</u> Vol. 8. No. 3, <u>Spring 1968.</u>

Table VI

MEADOWS: RATIOS OF TOTAL ACTUAL COST TO TOTAL ESTIMATED COSTS FOR 59 PROJECTS FROM TWO CHEMICAL LABORATORIES

Project Outcome	Number of Projects	Ratios
Chemical Lab. A		
Miscellaneous and Technical Failure	7	2.55
Commercial Failure	11	1.28
Commercial Success	12	0.94
	26	
Chemical Lab. B		
Miscellaneous and Technical Failure	4	3.84
Commercial Failure	12	4.25
Commercial Success	17	1.27
	33	

Source: Amended from Table II in D. Meadows, Industrial Management Review, Spring, 1968.

His general conclusions again show evidence of the existence of biases in estimation. The ratios of actual costs to estimated costs show over-optimistic biases of between $1\frac{1}{4}$ to 4 times for projects that were either technical or commercial failures but for projects that were commercial successes, actual and estimated costs tend to be very similar. It should be noted that for the chemical laboratories the major source of cost overruns were projects sponsored by the laboratory research staff themselves and smallest for projects sponsored by customers. This result is not surprising given the difference in technical difficulty that usually exists between laboratory and customer sponsored projects. It appears also that the ability of managers to predict the probability of technical and commercial success is limited, although they are far more able to get reasonable predictions of technical than commercial success. However, since estimates of probabilities are fraught with difficulties in interpretation and cannot strictly be verified, not much reliance should be given to these findings. Meadows does not present any evidence on the extent to which laboratory management can successfully predict the level of net profit or benefit likely to be achieved from a project, doubtless this will be reported in later analyses.

Allen has carried out a small study of the accuracy of forecasts in novel projects in a number of chemical laboratories[9]. He collected seven project case histories and attempted to measure the errors in forecasts by comparing them with the actual results. He also tried

---

9. D. H. Allen and P. J. November, "A Practical Study of the Accuracy of Forecasts in Novel Projects", Tripartite Chemical Engineering Conference, Montreal, September 1968.

to find out which of the various factors contributing to the financial outcome of a project significantly affect the eestimation of expected financial outcome because of errors in the initial forecasts.

His findings show that in four cases out of seven, cost forecasts tend to optimistic, in two cases pessimistic and in one case very slightly optimistic. These results tend to confirm the optimistic biases uncovered in Meadows' work but are not conclusive. It may well be that particular organisation structures generate different biases in forecasts and that the studies so far may have reported predominantly those organisations which a tendency towards over-optimism in forecasting. Only a statistically representative sample of firms will allow us to confirm tentative hypotheses about cost over- estimation. It is virtually impossible, given the understandable desire of firms to guard their corporate security, to obtain co-operation for a broadly based statistical sample. We must, therefore, be content to continue the case study work but extract the maximum possible amount of relevant information from each in order to make further progress.

Allen's analysis also gives us some evidence on forecasts of completion time and eventual benefit (profit, sales volume and price) from projects. However, because the firms in his sample obviously differed in their forecasting practices, time and sales volume estimates are not available for every case. In those cases where evidence is available forecasts of benefit are in all cases optimistic but time estimates tend to be much more accurate. Examination of the behaviour of forecasts of costs and benefits through time shows that it is only at a late stage in a project's development life that uncertainty in most of the forecasts is substantially resolved. Predictably, Allen finds that errors in the forecasts of benefit variables i.e. price and sales volume can affect the project's predicted financial outcome considerably but that errors in the various cost components, research and development, raw materials, etc., are also important. These results suggest that ratio type cost/benefit indices may produce incorrect measures of the attractiveness of potential projects and thus seriously invalidate any project selection decisions based on them.

6.2 Summary

The studies undertaken on military research and development viz. Marshall and Meckling and Peck and Scherer, show that initial estimates of cost are very optimistic and that time slippages in project completion occur very frequently. Although satisfactory performance is achieved it is often obtained at the expense of time slippage and increased cost.

The evidence from the industrial studies viz. Mansfield, Meadows and Allen is not consistent. Mansfield's equipment laboratory turns out to be well organised and error in forecasts of costs is very small. Further, even though time objectives are often unfulfilled most of the slippage is explained by changes in the individual project's nature and staffing . Meadows finds large errors in forecasts in his chemical laboratories and these tend to be of the same order for cost as the military research and development studies. Further, errors in forecasts of commercial and technical success are significantly large though much greater in the area of predicting commercial success. Allen's evidence for seven chemical projects tends to be similar to the laboratories in the Meadows study, viz. in general, optimistic biases in cost estimation and in the prediction of likely benefits arising from commercial adoption of the project's results.

It is reasonable to conclude on the basis of the existing evidence that in government sponsored research and development there tend to be over-optimistic estimates of likely costs and times to project completion. In commercial research and development errors in forecasts would seem to be a function of the type of industry, the product produced by the firm and the organisation structure of the individual firm. Firm conclusions are limited by the paucity of evidence. However, as more case studies are undertaken our understanding of research and development across different industries and firms will improve. It is in this spirit that the retrospective analysis in the next chapter of some of the research and development work of two firms in the electronics industry is presented.

PART III

Chapter 7

RETROSPECTIVE ANALYSIS OF PAST R & D PROJECTS IN TWO FIRMS IN THE ELECTRONICS INDUSTRY

7.0 Introduction

In the previous chapter we looked at the range of published studies on the retrospective cost effectiveness analysis of both government and privately financed research and development. This chapter is concerned with the usefulness of retrospective cost/benefit analysis in enriching our understanding of the economic characteristics of the development process. The analysis differs from our view in Part II of the formal and informal processes of decision in R & D because it seeks to evaluate the actual performance of the R & D systems in Firms A and B. In particular, Part II allows us to develop some hypotheses about the characteristics of the development process but it is only in this part of the work that they can be given operational meaning. Our objectives in the analysis presented here are to improve our knowledge of the economics of the development process by highlighting and discussing the problems encountered in development work. Thus, we try to build on our basic knowledge of the environmental and organisational structures of Firms A and B and their formally stated decision processes in R & D work to improve our understanding of the nature of the development process and the alternative strategies that are possible for the research director. The distinctive feature of the analysis is that we are trying to give a depth analysis of R & D in two firms by means of a continual case study of its environment and actual decision problems. Our underlying aim is, thus, to help move towards a better and perhaps normative theory of development. We begin this chapter with a discussion of the methodology of the cost benefit study and the sample of projects obtained for subsequent analysis. The central core of the chapter is concerned with the accuracy of forecasts made in relation to R & D projects and the nature of uncertainty in the development process. The evidence obtained is then compared with the published material evaluated in Chapter 6.

7.1 Methodology

The approach adopted in both A and B was to establish a representative sample of past projects undertaken by the firms and then to try to piece together from formal records, accounting data and discussions with project engineering personnel how these projects started and evolved through time. Given this reconstruction we can then carry out analyses of forecast error, of the resolution of uncertainty through the life of the project and of the reasons for changes in the technical and commercial objectives of a given project.

7.2 Data

In the following section we present a brief description of each of the projects evaluated in firms A and B. This description is necessarily limited by the desire to avoid identifying the firm or the exact nature of the project. The description is given primarily to provide an awareness of extraneous factors to be borne in mind in considering results of the later analysis.

Project 1A

One of a projected family of instruments for electronic measurement. The objective of pursuing the concept of the family of instruments was a result of a company plan to produce a range of test instruments in an area not previously exploited by the company. Market potential was considered by the company to be considerable and the expertise within the research and development laboratory available to carry out the work.

Project 2A

A complementary instrument to 1A produced to extend the product line.

Project 3A

The final member of the first phase of the series 1A, 2A set of instruments. This was produced to provide a complete measurement system for the customer and to provide training for existing engineers in the technical area before the launching of the second phase of this system of instruments. Again, market potential for the system was estimated to be considerable.

Project 4A

A measurement instrument sponsored and planned by the laboratory management to follow on and replace an existing instrument. The modifications were designed to improve the capability and performance of the device. The market potential was thought to be large.

Project 5A

A re-design of an existing instrument for a specific customer. The request for the research to be done emanated from the sales division who considered that the market offered was profitable to the company.

Project 6A

An instrument specifically planned by the laboratory management to place the firm in a new area of electronic measurement. Again, the market was considered to be very large and the measurement area one with great long term potential. As a result the project was felt to be a small extent a learning exercise as well as a profitable venture for the company and its technical staff.

Project 7A

To design an electronic measurement to meet known existing demand. Again a family of instruments was planned and in this case it is considered reasonable to view them as one rather than three distinct projects. The idea for the project was generated within the laboratory.

Project 8A

An instrument designed and planned to be used as a complementary instrument to an existing successful product marketed by the firm. The market for the instrument was thus considered to be steady but not considerable.

Project 9A

An instrument designed as a result of technical "fall-out" from the project 1A series. Considered to have a useful market potential and overall benefit for the firm.

Project 10A

An instrument designed specifically to a special contract from a customer. Sales department considered the development would be extremely profitable for the firm and the laboratory regarded the development work as being a fairly simple task.

We now present four projects which were shelved by the firm. Owing to the fact that records for shelved or failed projects are very difficult to trace the documentation or description in these cases is not up to the standard of the previous sample of 10.

Project 11A

An electrical measurement instrument to fill a gap in the firm's product line. Market potential uncertain and ultimate benefit to the firm considered to be not very great.

Project 12A

An extension of the project 6A range of instruments. Considered to have both good market potential and profitability prospects.

Project 13A

An instrument designed to a contract specification from an outside customer. Both market potential and benefit were calculated to be large and the involvement in a new measurement technique technically appealing.

Project 14A

A fall-out from the 1A series of instruments. Undertaken largely because of the spin-off even though market potential and benefit were estimated to be barely satisfactory.

The above sample of projects is considered to be a representative sample of the work undertaken by the firm over the five-year period 1963-1968 including the early months of 1969. From the description of the projects and the overall description of the firm given in the second part of the thesis, it is clear that the firm has a formal evaluation and review system for research and development projects. Briefly, if the research and development manager decides that a project idea is worthy of further consideration he requires that a preliminary evaluation of specification, design and project economics is carried out. If this proves prositive the project engineer assigned to the investigation phase of the project must estimate certain economic factors; cost, eventual quantity sold, price and profit rate and calculate a preliminary net benefit/cost ratio for the project. Then, if the value of this ratio is greater than some minimum corporate target a decision is generally made to recommend inclusion of the project in the research and development work of the firm subject to the availability of resources. The nature of this project selection process should be borne in mind in reviewing the tabular analysis of retrospective data.

Project 1B

This project has been created from a large number of individual projects which on individual analysis might not appear profitable but when viewed as a system were attractive to the management of the firm. The system embraces a bread and butter range of measuring instruments of high quality with the advantage of cheapness and reliability at the expense of extreme technical sophistication. The family of instruments has been continually developed and new additions, modifications etc. are introduced to sale at the same time as development is proceeding.

Project 2B

This project has largely been sponsored by outside contract. It is an instrument in a new area for the firm and is intended to compete with a couple of existing products which do not have the performance and specification of the new instrument. The instrument was an attempt to build a bridgehead for the firm in the area with a view to further long term expansion. The attraction of the project was enhanced for the firm because a large proportion of risk capital was provided from sources external to the firm.

There are a number of other projects that could be presented but the level and quality of past records is not sufficient to maintain the same standard of analysis as with previous projects. The problem with Firm B is that records of expenditure on R & D projects have only recently been started and market and cost evaluations of projects are in most cases no more than "ballpark" estimates. Analysis based on such data would obviously have spurious validity.

7.3 Analysis of Data

In this section we shall try to assess:

1) The accuracy of forecasts of variables related to the projects,

2) The change in these forecasts through time and the resolution of uncertainty;

3) The usefulness of the return factor index of Firm A in giving a valid measure of worth of project and predicting the eventual financial outcome of a project.

7.3.1 Forecast Accuracy

Typically, the decision to include a project within a firm's R & D portfolio is dependent upon a preliminary process of evaluating the worth of the project to the firm. The methods by which firms evaluate projects vary from the fairly informal, rough appraisal of a firm like B to the more formal economic appraisal of factors such as likely cost and revenue cash flows and the calculation of a rate of return factor. An example of the latter type of approach is the procedure adopted by Firm A.

If a firm calculates a return factor it requires estimates of economic factors as inputs to this calculation. It can be seen fairly easily that a return factor of the form Net Revenue/Cost can give misleading values if the forecast inputs are not accurate. If a decision to undertake a project is based solely on the figure of merit given by a return factor without allowing for inaccuracies in the forecasts of inputs the firm may commit heavy expenditures to a worthless project and reduce the value of its total research work. We shall not discuss here whether firms should use return factors to aid them in their project selection decisions. We shall take the view that whatever method they use to appraise a project, better decisions will come on average from better forecasts of market and cost factors.

In Table 1 below we present ratios for FIRM A of the earliest available estimat es of the factors, i.e. those on which decisions were based, to the actual value that eventually occurred. Firm A evaluates how much the development will cost (and how long it will take), how many units of the end product are likely to be sold over an estimated life for the product and what the market price for the product will be. It should be noticed that colums 7, 8 and 9 in the table assess the degree of technical advance (SMALL, MEDIUM OR LARGE) of the end product, the final status of the project in terms of technical and commercial success and the source of the idea to develop the product (L = Laboratory, C = Customer). For almost all the projects it is too early yet to assess whether the engineers assessed the likely market life for the end product correctly.

Some comments must be made at this point about a number of the items presented in Table 1. First, column 3 is obtained by adjusting the ratios in Column 2 for the influence of changes in price levels. The adjustment is thus the familiar one for the effects of inflation and it was carried out in the following manner. From previous accounting records of cost breakdowns for the R & D department the ratio of overhead costs, including occupancy costs, wages and salaries, to materials costs was approximately one to one. With this one to one relationship established official statistical publications were then consulted to find out the rate of increase of earnings and materials costs over the period of study. Tables in the Monthly Digest of Statistics for the average earnings of all employees in the engineering and electrical goods industry and for the wholesale price of materials used in the engineering and electrical goods industry were used to measure the rates of change of earnings and materials costs over the period of study. It was further assumed that overhead costs could reasonably be considered to be strongly correlated with earnings costs and, therefore, could be adjusted by the measure for the rate of change of earnings. Then, for each project an index was constructed giving equal weight to overhead and materials costs to allow for changes in price levels over the development period of that project.

It is important to remember at this point that the measurement of ratios of final to initial values of cost and other factors is complicated not only by the effects of inflation but also by changes in project objectives and the estimated magnitude of the production run that become apparent during the development period. Where it has been considered necessary to adjust for such changes as this the adjustment has been carried out. However, the adjustment is subjective in two respects. First, the situations in which other factors have influenced costs or other factors are judged subjectively by the investigator and second, the magnitude of the adjustment necessary to allow for the bias introduced can only be subjectively assessed. This is why Marshall and Meckling found it necessary in their work to provide two sets of adjusted estimates one constructed by Eugene Brussell and the other by Robert Summers. They commented that the tricky nature of the adjustment process and the element of subjective judgement necessarily mean that no two estimators will give the same weighting to the elements in the adjustment process.

The seventh column in the table on the degree of technical advance of the projects was obtained by asking the research and development manager and the project engineer for each project to evaluate the technical nature of the project and assess it on a three point scale, small, medium and large. The eighth column in the table was obtained from the company accountant who assessed whether the final return factor for the project did or did not meet the corporate targets. The final column on the source of the project idea was obtained through interview and perusal of project records. It is to be noted that Table 1 does not include the data on the four technical failure projects of Firm A. These are treated separately because of their unique characteristics.

Table 1

FIRM A - PROJECTS 1 - 10 - UNADJUSTED RATIOS OF EARLIEST ESTIMATES OF FACTORS TO THE FINAL VALUE

Project	Cost	Adjusted Cost	Quantity Sold	Time for development	Price	Degree of Technical Advance	Status* of Project	Idea Source
1	2.76	2.37	1.43	1.15	1.22	M	TS, NCS	L
2	2.74	2.35	2.00	1.15	1.52	M	TS, CS	L
3	2.72	2.33	1.71	1.15	0.87	M	TS, CS	L
4	1.05	0.87	0.16	1.0	1.00	S	TS, NCS	L
5	0.7	0.33	0.66	1.4	0.83	S	TS, CS	C
6	3.66	3.42	1.18	1.0	3.42	L	TS, CS	L
7	1.11	1.04	0.13	1.4	1.92	S	TS, NCS	L
8	1.53	1.44	0.2	1.5	0.46	S	TS, NCS	L
9	2.54	2.54	0.5	1.0	0.57	S	TS, NCS	L
10	3.77	3.52	0.25	1.2	0.94	S	TS, CS	C

* Note TS denotes TECHNICAL SUCCESS

CS DENOTES COMMERCIAL SUCCESS

NCS denotes NOT COMMERCIAL SUCCESS

The relevance of the information in Table 1 is that it shows the innacuracies that exist in early forecasts of various factors and enables us to assess their extent and influence on the revenue/cost ratios.

Specifically, the fifth column in the table indicates that the firm is well able to forecast with reasonable accuracy how long the research and development work will take. This result is explained in large part by the firm's policy of trying to meet deadlines wherever possible and its adoption of network analysis techniques for project planning. Trade offs of extra resource inputs are frequently tolerated and accepted by the firm in order to fulfil time targets.

It is equally clear from the results in column 2 that in most cases initial cost forecasts tend to be far smaller than actual final cost values. A contributory factor is clearly the extent of extra resources that are often injected into a project in order to ensure completion by a given date. In addition, changes in price levels and expected output levels can have a significant effect. Nevertheless, the results indicate considerable weaknesses and overoptimism in the forecasting of costs. This result is consistent with the nature of overoptimistic biases found in most of the existing studies andis of greater importance here because the firm has a well organised information system and is efficiently run.

On the revenue side in most of the cases it is clear that early estimates of quantities sold tend to overstate the actual final position by a considerable amount. This highlights the fact that marketing a new R & D generated product (i.e. knowing its likely market) is difficult and past data on sales are not likely to be helpful unless the firm is selling in well-defined technical market. Unfortunately, well-defined markets exist in very few cases. Despite the difficulties in quantity estimation the extent of the error can be explained in part by biases which engineers in A admitted were widespread when they were asked to evaluate the worth of a project by some form of return factor index.

It is interesting to consider whether the extent of accuracy in the estimation of the various factors related to a project's worth varies with the degree of technical advance of those projects. Table II provides a breakdown of estimation performance by the magnitude of technical advance of a project.

Table II

FIRM A - MEAN AND STANDARD DEVIATION OF RATIOS ANALYSED BY DEGREE OF MAGNITUDE OF TECHNICAL ADVANCE

(values in the table are mean or average ratios)

Economic Factors	Small (6 observations)		Medium and Large (4 observations)	
	Mean	S.D.	Mean	S.D.
Cost	1.78	1.16	2.97	0.46
Adjusted Cost	1.62	1.19	2.62	0.57
Quantity Sold	0.31	0.21	1.58	0.36
Price	0.95	0.22	1.75	0.06
Time	1.25	0.52	1.11	1.14

It is clear from this analysis that there are differences in forecast error between projects of limited and great technical difficulty. Because we have few cases of large technical advance it is more relevant to aggregate the cases of medium and large technical advance in the table. Actual costs tend to be twice as much as initial estimates in the case of small technical advance and about three times in the case of medium to large technical advance. Even if allowance were made for inflation over the development period the relative difference between the small and medium to large cases would be of approximately the same magnitude. This result suggests that cost forecasts are more accurate when the degree of technical uncertainty is small and vice-versa.

It is difficult to come to firm conclusions about inaccuracies in sales (or quantity sold) forecasts. When the technical advance of a project is small, on average we find that final sales over the period are only about one-third of the initial estimate. On the other hand medium to large technically advanced projects tend to produce sales greater than initial estimated values by a mean factor of about half. Certainly technically advanced products will tend to define a market of their own and not often be subject to severe competition. Projects of a more limited degree of technical advance tend to be improvements to existing ranges or "gap fillers" in the firm's product line and thus are subject to competition from a number of other firms already in the market. A simple explanation of the results produced in the table may merely reflect inability to estimate market size either in the case of a new technically advanced instrument when other firms may be doing research designed to produce a similarly technically advanced instrument at roughly the same time or in the case of small detailed improvements to an existing product when consumers may prefer a more limited specification or one of the range of instruments available from other firms. However, if we had more observations we might have found that if firms can afford to do high risk, technologically advanced R & D and succeed in their development work, their eventual market might be much larger than if they concentrated on a low risk diversified R & D portfolio. A conclusion of this nature would be a statement if true of the extent of research economies of scale.

Price forecasts seem to be very accurate in the case of small technical advance but underestimated initially in the case of medium to large levels of technical advance. Because medium / large levels have greater degrees of technical uncertainty we have seen already that cost estimates tend to be severely underestimated relative to projects with much smaller levels of technical advance. Since firm A sets its prices by means of full costs plus a mark-up it is not surprising that final prices are greater than initial estimated prices in cases of high technical advance. In addition, where technical advance is larger the market is less well defined and this further complicates meaningful estimation of prices at an early stage in the development life of a project.

As we have noted already there is no real difference between projects of different levels of technical advance in their ability to fulfil time objectives. Nothing can be inferred from this fact other than it is a direct result of 2 factors, first the strict control system for R & D adopted by the firm and, second, the firm's policy to complete its R & D work on time even if extra money and resources have to be incurred.

A further analysis of the figures in Table 1 by extent of final commercial success provides an interesting picture. This is shown in Table III.

Table III

BREAKDOWN OF PROJECTS INTO THOSE WHICH WERE EVENTUAL COMMERCIAL SUCCESSES AND FAILURES. ANALYSIS OF FORECAST ACCURACY ON ECONOMIC FACTORS BETWEEN THE TWO CASES.

	Commercial Success					Commercial Failure				
	Mean & S. D. of Ratios for					Mean & S. D. of Ratios for				
	Cost	Adjusted Cost	Quantity	Price	Time	Cost	Adjusted Cost	Quantity	Price	Time
Mean	2. 72	2. 39	1. 16	1. 52	1. 18	1. 78	1. 65	0. 48	1. 03	1. 21
Standard Deviation	(1. 23)	(1. 28)	(0. 23)	(1. 1)	(0. 01)	(0. 81)	(0. 76)	(0. 55)	(0. 58)	0. 22
	(based on five observations)					(based on five observations)				

It can be seen that commercially successful projects exhibit greater errors in forecast estimates than non-commercially successful projects except for forecasts of eventual market. This can be explained partly because three out of the five commercially successful projects represent significant degrees of technical advance compared with only one of the non-commercially successful projects. We have seen that high technical advance projects tend to define markets of their own and no matter how much the escalation of costs these are regained by the firm via a full cost pricing policy. The evidence for this firm suggests that to be commercially successful an useful R & D strategy would be to engage in an R & D programme with its objective as the development of technically advanced rather than bread and butter projects.

It has not been considered worthwhile to provide figures of the initial and final estimates of the various economic and time factors for the technically unsuccessful projects of Firm A's portfolio. The reason is a simple one. These projects have been terminated for different reasons: poor initial feasibility, shortage of skilled labour resources, rapid cost escalation and so on. As such comparison of "final" estimates against initial ones is not meaningful because "final" does not relate to an unique point in time (such as the end of the development period with technically successful projects) and thus comparison of results with other more successful projects is rendered worthless.

However, we present in Table IV beneath ratios of the latest available estimates of cost for each of the four projects before termination to the initial estimated total development cost and a short explanation of the reasons for termination of the project.

Table IV

COST RATIOS

Project	Ratios	Reason Given
11	1.04	Uncertain market; low return factor
12	1.82	Rapid escalation of initial cost estimate
13	2.1	Political difficulties with contract
14	1.1	Instrument not viable in market

Too much reliance should not be placed on the reasons given for project termination because observation has shown them to be convenient rationalisations and not statements of reality. In fact, project 11 has now just been reinstated in the laboratory largely because personality differences about the relevance of the project have been resolved. Further, project 12 is now again under active consideration because sufficiently skilled engineering resources have become available. It is the view of this observer that if project

12 had been undertaken at the time of its first inception the company would have had a huge commercial success in the light of the market reaction to project 6's final end product. Thus, for comparative purposes we cannot say much about projects that were technical failures in this firm. It is surprising in view of the former argument that Meadows in his study analyses ratios for a number of projects that turned out to be failures or were terminated. Obviously, since reasons for failure or termination are never the same in each case and are not necessarily meaningful in technical terms it is misleading to give information on forecast ratios in these cases.

The evidence available from Firm B on forecast accuracy is for reasons that were made clear in Part II far less detailed and comprehensive. It is useful to remember that records for firm B on R & D projects have until recently been kept on ly in those cases where outside risk capital is a major source of finance. If we take note also that appraisal of projects is very informal and economic estimates related to R & D projects are no better than "guesstimates" then it is clear that an analysis as detailed and thorough as that for Firm A is not possible in this case. However, we can only say here that Project 2 B does provide us with some estimates of cost, price and sales per annum because the sponsoring agency required information of this nature when it gave the risk capital and subsequently when it reviewed the progress of the project.

The estimates made for this project should be considered as being an example of the best possible estimating behaviour - "bread and butter" R & D projects are approved on the basis of highly informal and speedy subjective evaluations. The information available from Project 2B is given in Table V below.

Table V

FIRM B: UNADJUSTED COST, PRICE AND SALES RATIOS OF FINAL TO EARLIEST ESTIMATES : PROJECT 2B

Factor	Ratio
Cost	2.25
Price	1.4
Sales	0.2

Note: The SALES ratio is based upon the first year's actual sales for the instrument and the initial estimated value of sales for that year.

This project can fairly be regarded as being technically advanced in nature so that the inaccuracy of cost estimation is understandable and perhaps a little bit smaller than with Firm A and the ratios obtained in other R & D studies. The price estimate inaccuracy is again of the same order as for a technically advanced project in Firm A and consistent with the level of cost escalation given the practice of full cost pricing in the firm. The short fall of actual sales, however, differs from the case of firm A in which the opposite occurred for technically advanced projects. The difference might be explained by the marketing oriented approach in new product planning present in Firm A. However, it is true to say that Firm B has had the same short fall experience with a couple of sponsored projects it undertook some years previously and which project engineers raised when the poor sales performance of 2B was discussed with them. Since we have concrete information on only 2B we should perhaps emphasise that discussions with project engineers in B about previous projects yielded the general impression of a tremendous lack of awareness of the importance of economic factors such as cost and sales of a project and where "guesstimates" of the values of cost and sales had been made they tended to be wildly inaccurate and almost random in comparison with the true value.

It is clear that with the degree of inaccuracy at present found in project appraisals, measures of worth of projects based on these estimates may give an incorrect assessment of the value of each project to the firm. Until forecasts can be improved adoption of selection techniques for R & D projects based on estimating likely financial rates of return must proceed with caution. In any case decision should never be made solely on the basis of the value of the rate of return factor and must be combined with technical and other relevant evaluations.

7.3.2 Uncertainty Resolution

Thomas Marshak[1] in discussing the nature of the development process considers it to be a process of uncertainty reduction or learning. This idea of the nature of the development process is one which is supported by earlier evidence in this thesis. In fact, the RAND Corporation through a number of its research personnel such as Marschak, Klein[2], Meckling[3] and Nelson[4] can be regarded as being the originator of this view of the development process. We need here to provide evidence about the nature of uncertainty in industrial development and parallel it with the RAND view of the military development process. Such a comparison is essential in view of RAND's development of the parallel path strategy for military research and development management. Basically RAND believes that uncertainty about any given project is so great initially that the most sensible strategy is to carry out R & D on a number of possible approaches to the project in parallel until design uncertainty is resolved sufficiently for the best approach to become clear to the research director.

Uncertainty is not so great in industrial R & D because of its applied nature and, therefore, we suspect that a parallel path strategy would not be useful for the management of most industrial R & D projects. However, it is of great importance for the industrial manager to know what faith he should place on forecasts and, in particular, to know at which stage in the development process they become reasonably accurate.

1. T. Marschak, "The Microeconomic Study of Development" Chapter I in Strategy for R & D by T. Marschak et al. (Springer-Verlag, 1968)
2. B. H. Klein, "The Nature of Military R & D" P1818 (Rand Corporation) 1960
3. B. H. Klein and W. Meckling, "An Application of Operations Research to Development Decision" Operations Research, VI (May-June 1958)
4. R. R. Nelson, "Uncertainty, Learning, and the Economics of Parallel Research and Development Efforts" Review of Economics and Statistics, 1961.

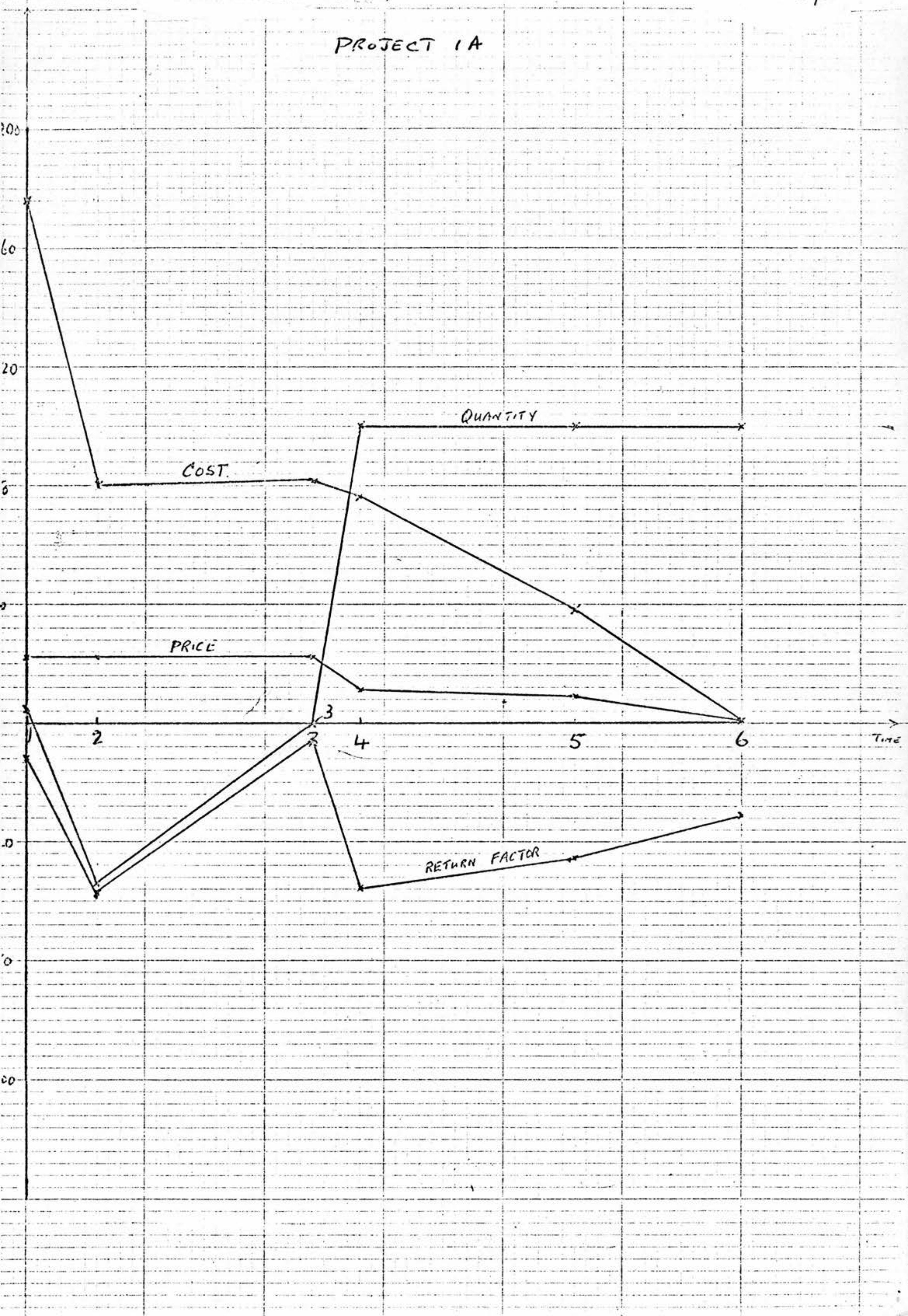
The only evidence available in this study about uncertainty resolution is from Firm A. In certain cases with technically unsuccessful projects the basis for their decision to suspend work on a project for an indefinite period has been stated (see Table IV) to be because the latest available estimates of cost, sales etc. present a clearer picture of the true worth of the project to the firm. Since the firm was never able to find out the true value of costs, sales etc. (because they never completed the R & D work) the firm's decision implicitly assumed that latest available forecasts present a more useful decision tool than initial forecasts. We have to ask whether this has been true of forecasts on technically successful projects.

A detailed analysis of the forecast evidence is presented below. This analysis consists of graphs of the behaviour of the forecasts of cost, quantity sold, price and the associated measure of worth, the return factor at discrete points within the development period. It should be noted that the number of points evaluated varies with the length of the project, the technical obstacles that occur and the routine need for forecasts. In fact, forecasts are typically made every four to six months and also when a significant problem, economic or technical occurs during the project's development. The variable plotted on the graphs presented below is the forecast inaccuracy where the degree of forecast inaccuracy is measured by the index :-

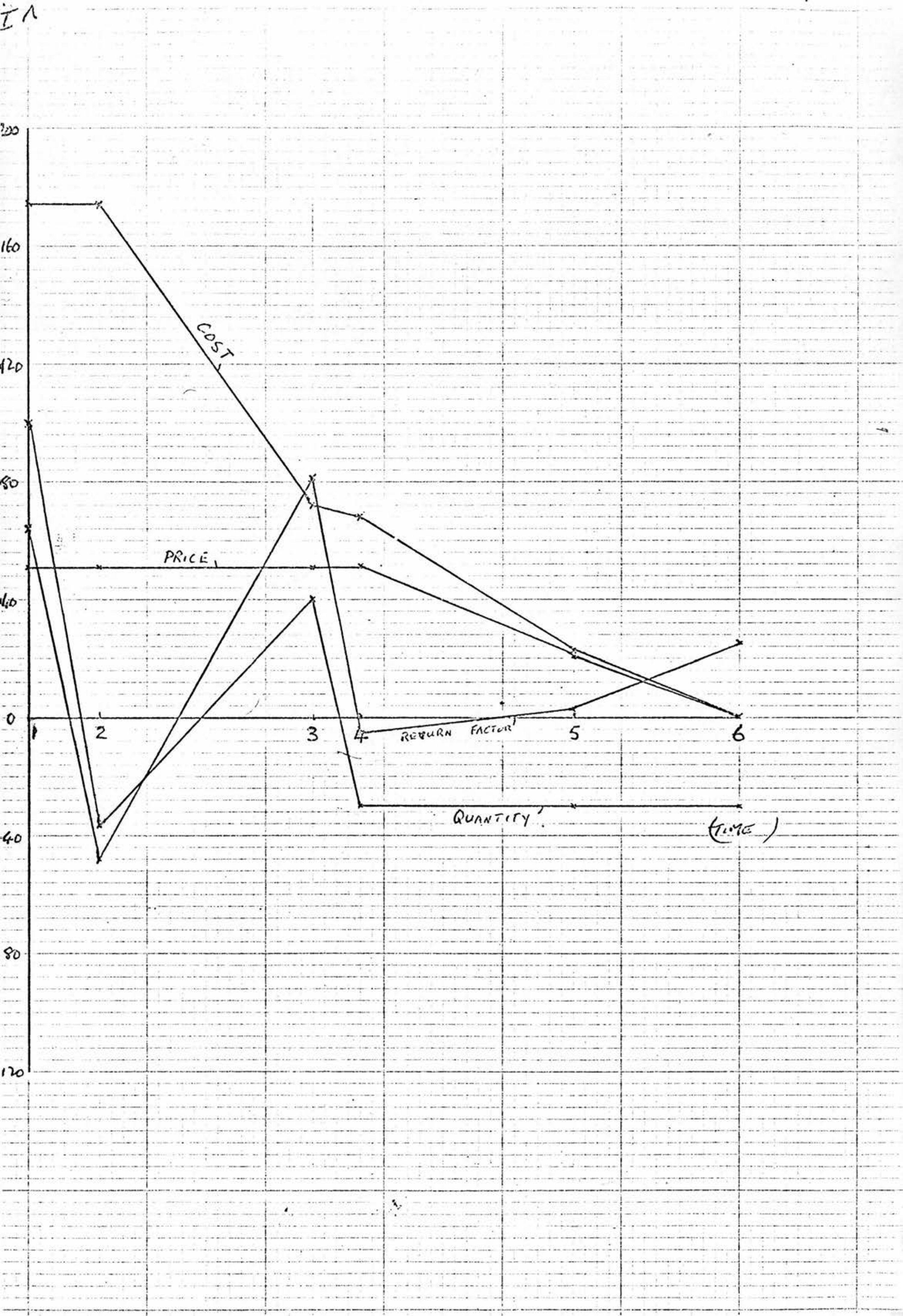
$$I = \frac{\text{Actual Value - Forecast Value}}{\text{Forecast Value}}$$

expressed as a percentage. We shall present the graphs immediately now and then discuss the findings that appear subsequently. In the tables which accompany the graphs we present the values of I for each factor on the 10 technically successful projects.

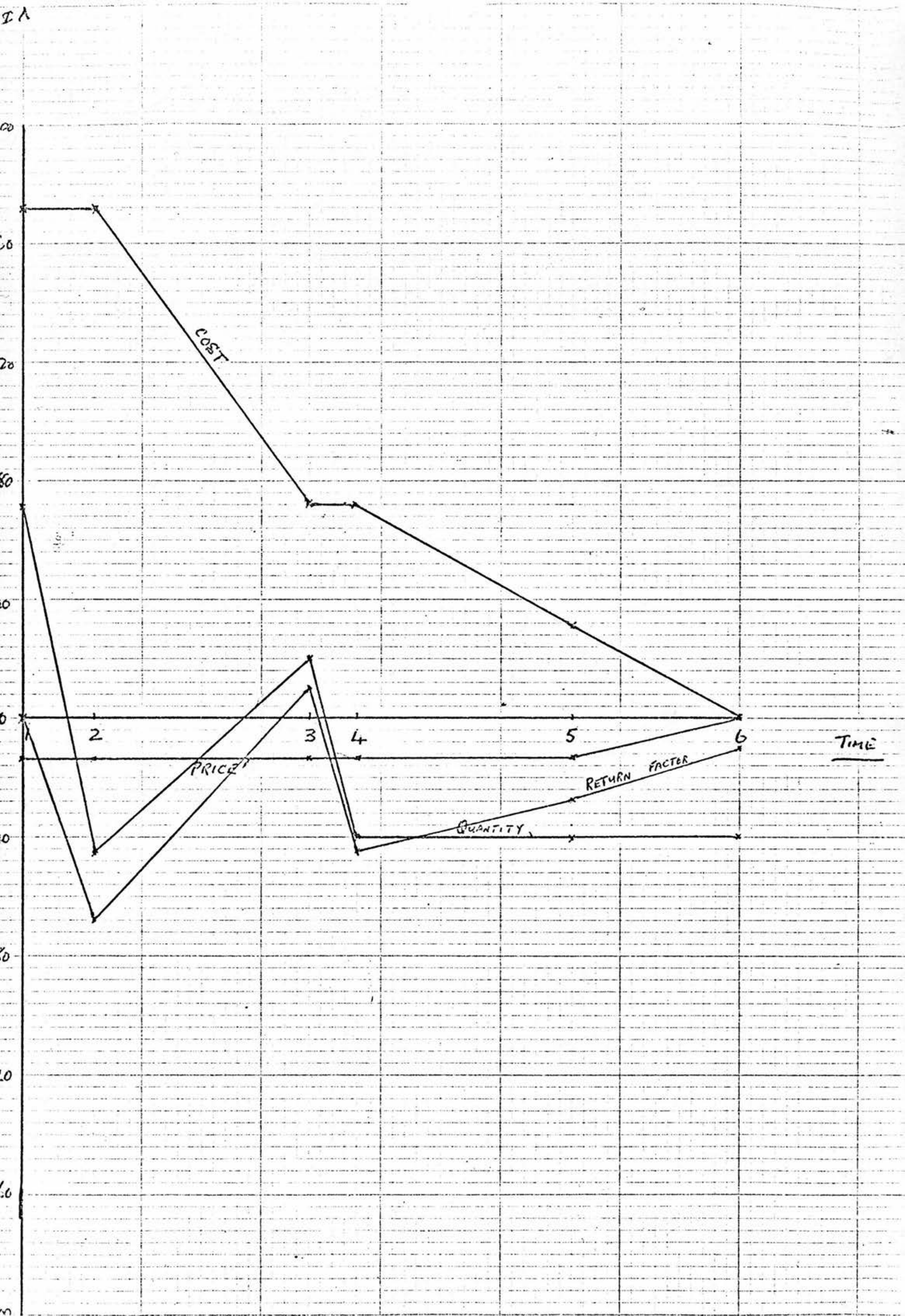
GRAPH OF I V TIME



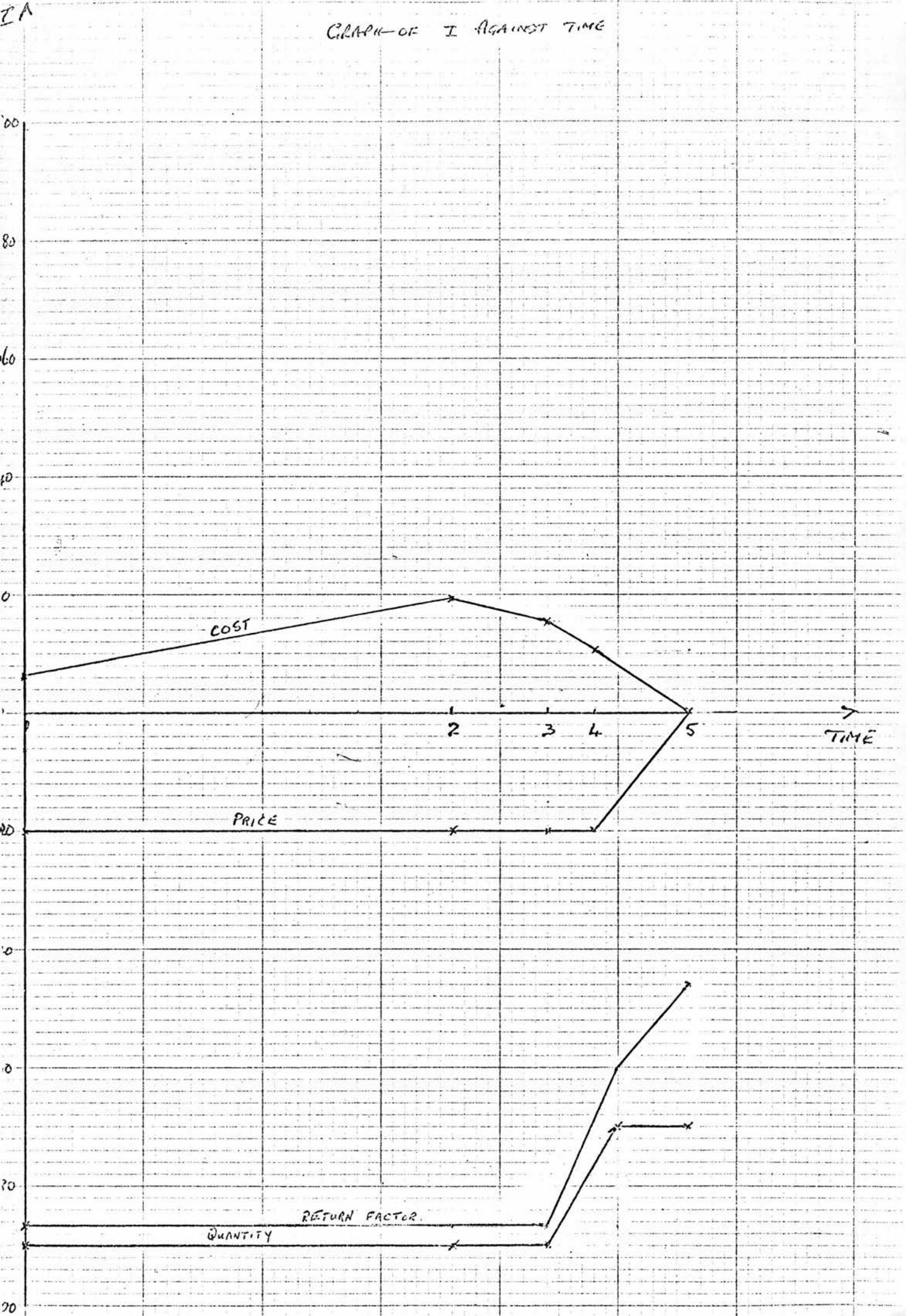
PROJECT 2A : GRAPH OF I AGAINST TIME



PROJECT 3A   GRAPH OF I AGAINST TIME

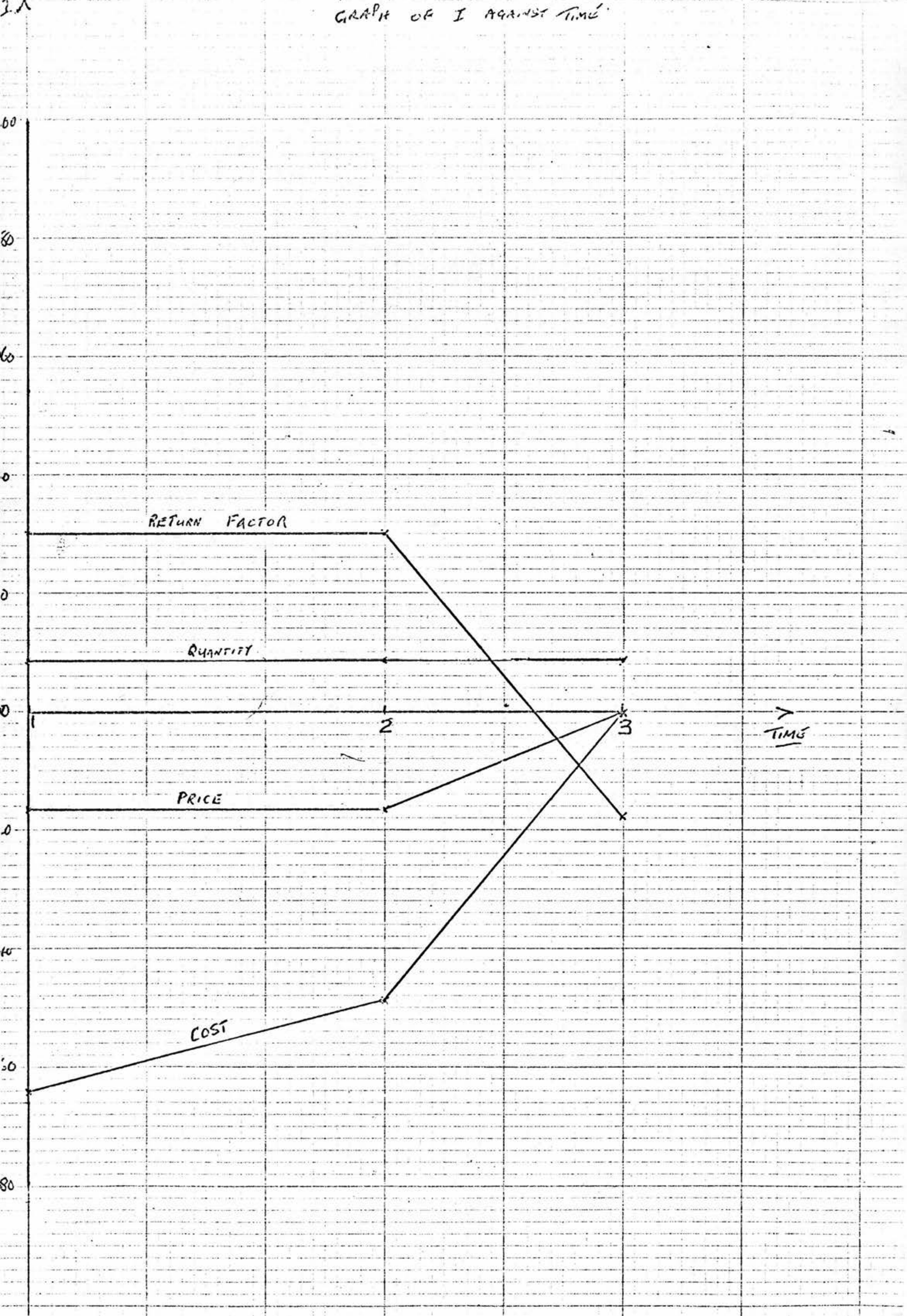


GRAPH OF I AGAINST TIME

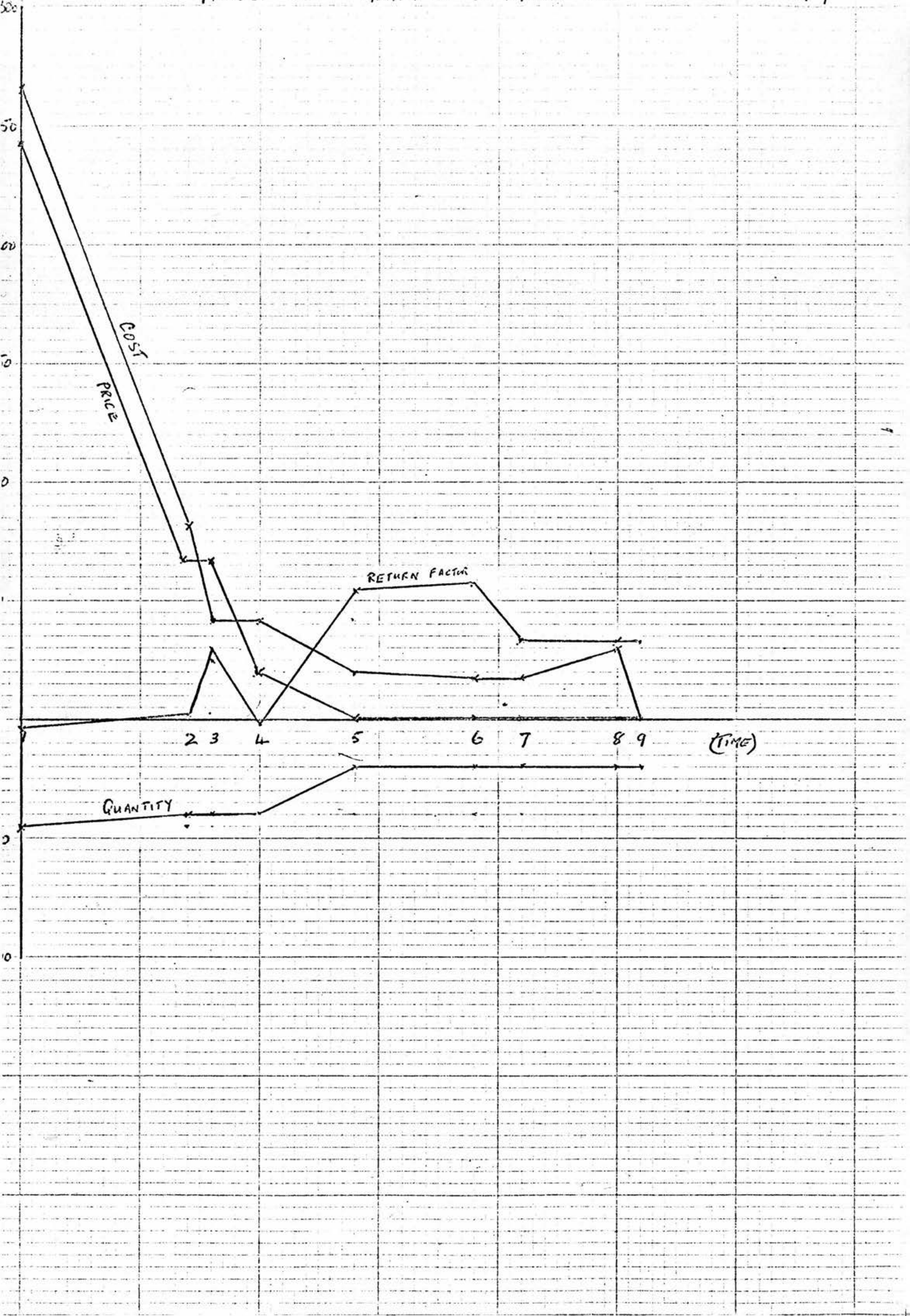


PROJECT 5A

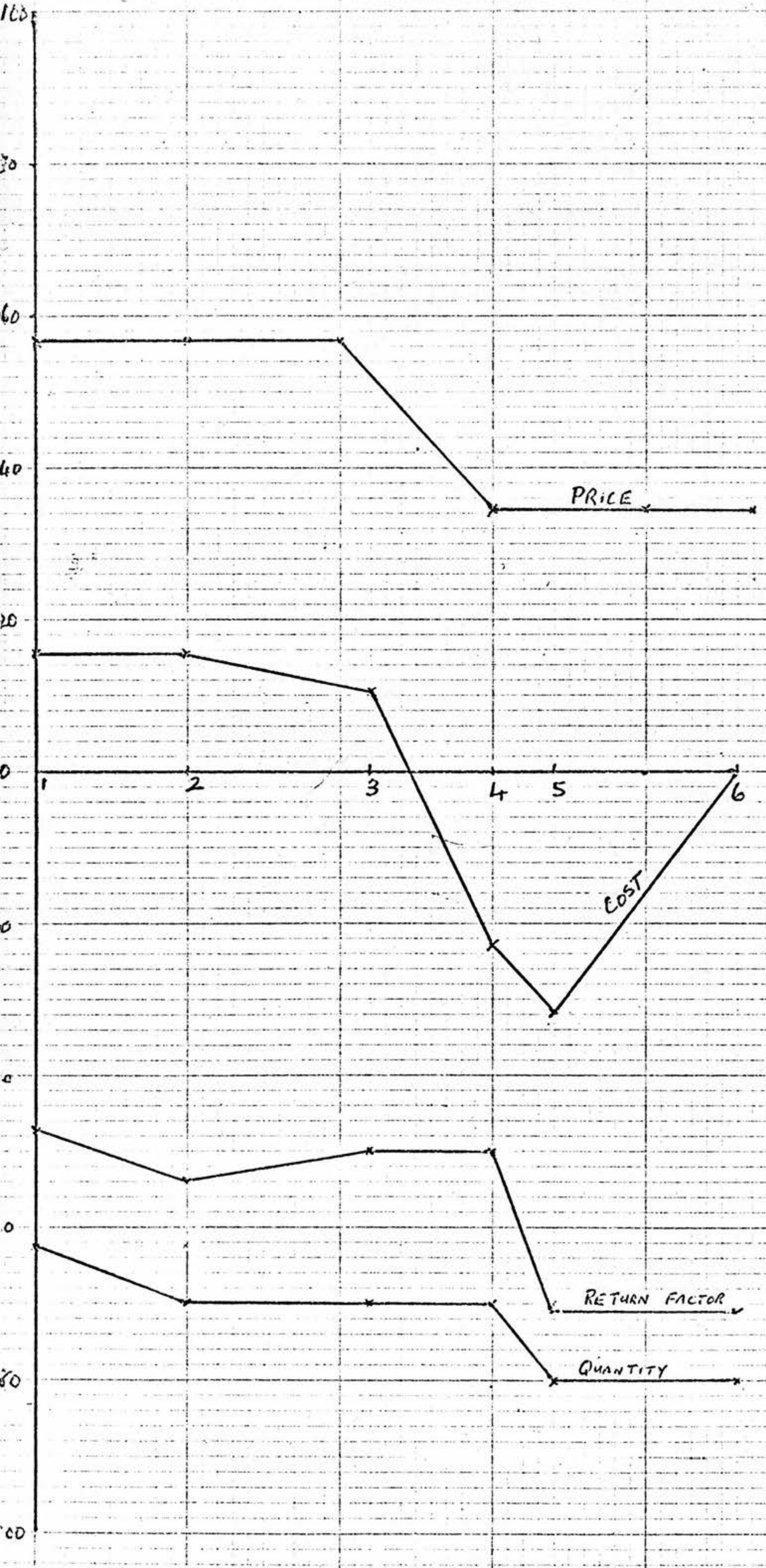
GRAPH OF I AGAINST TIME



PROJECT 6A GRAPH OF I AGAINST TIME

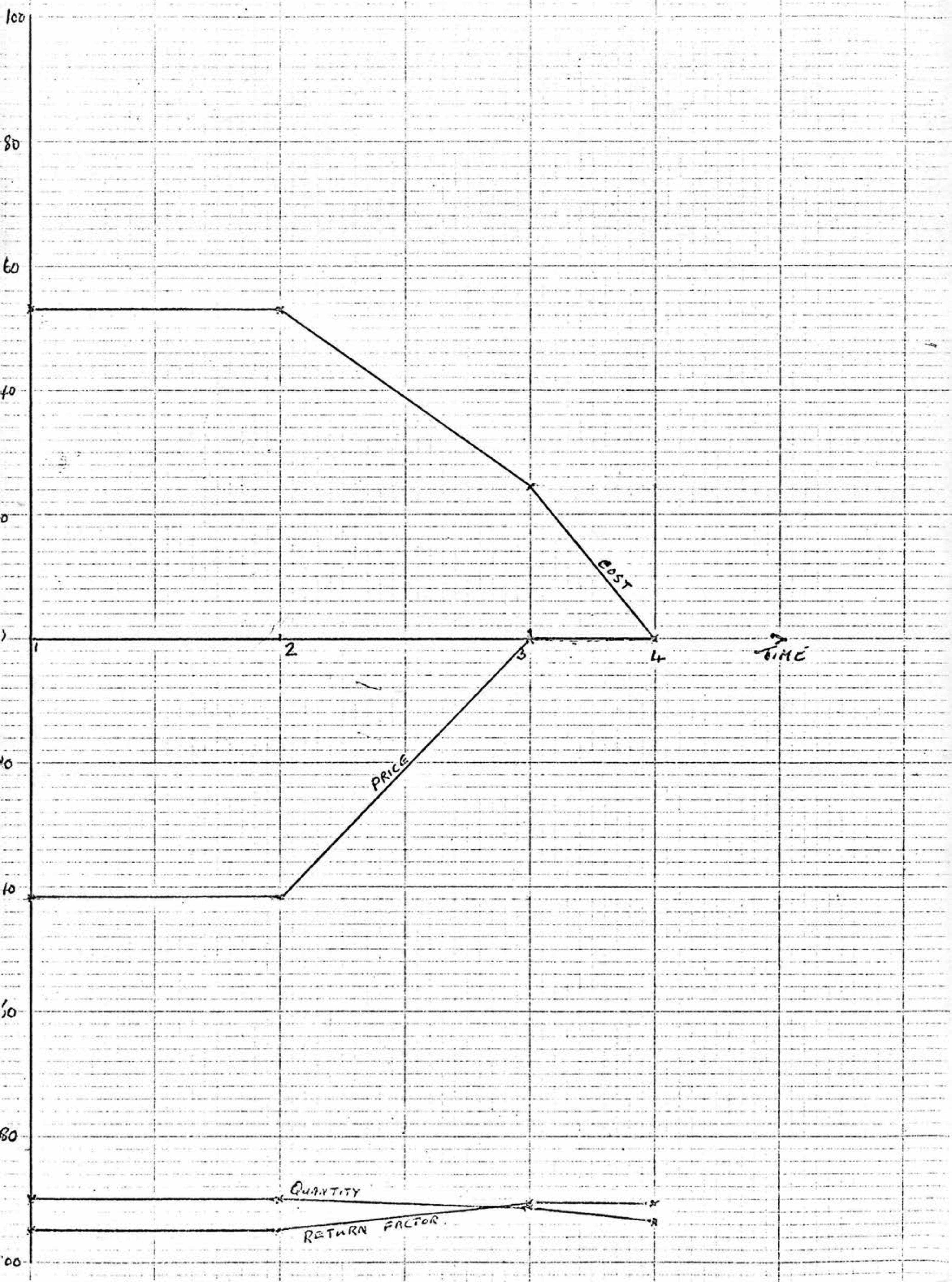


GRAPH OF I AGAINST TIME.



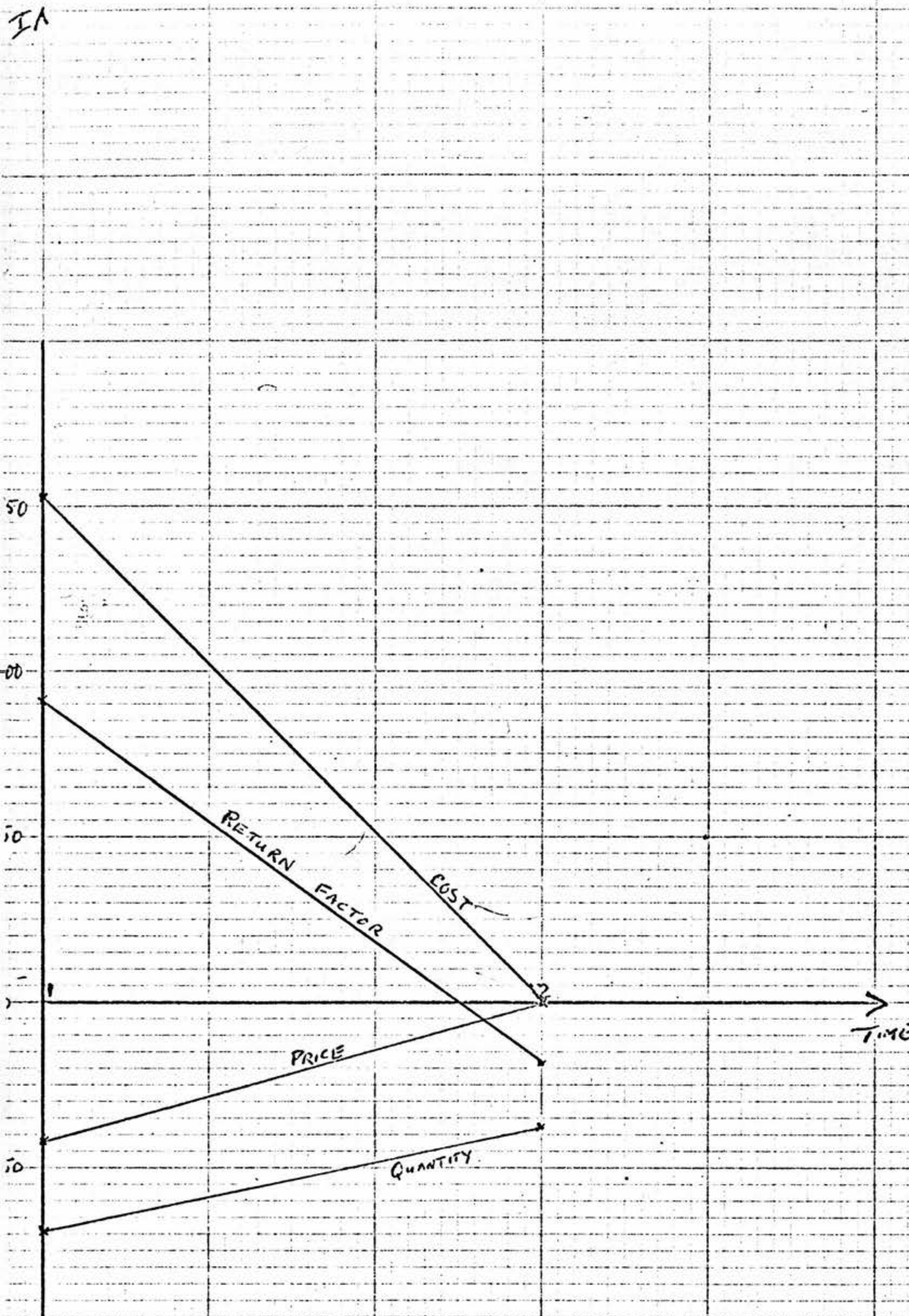
PROJECT $A

GRAPH OF I AGAINST TIME

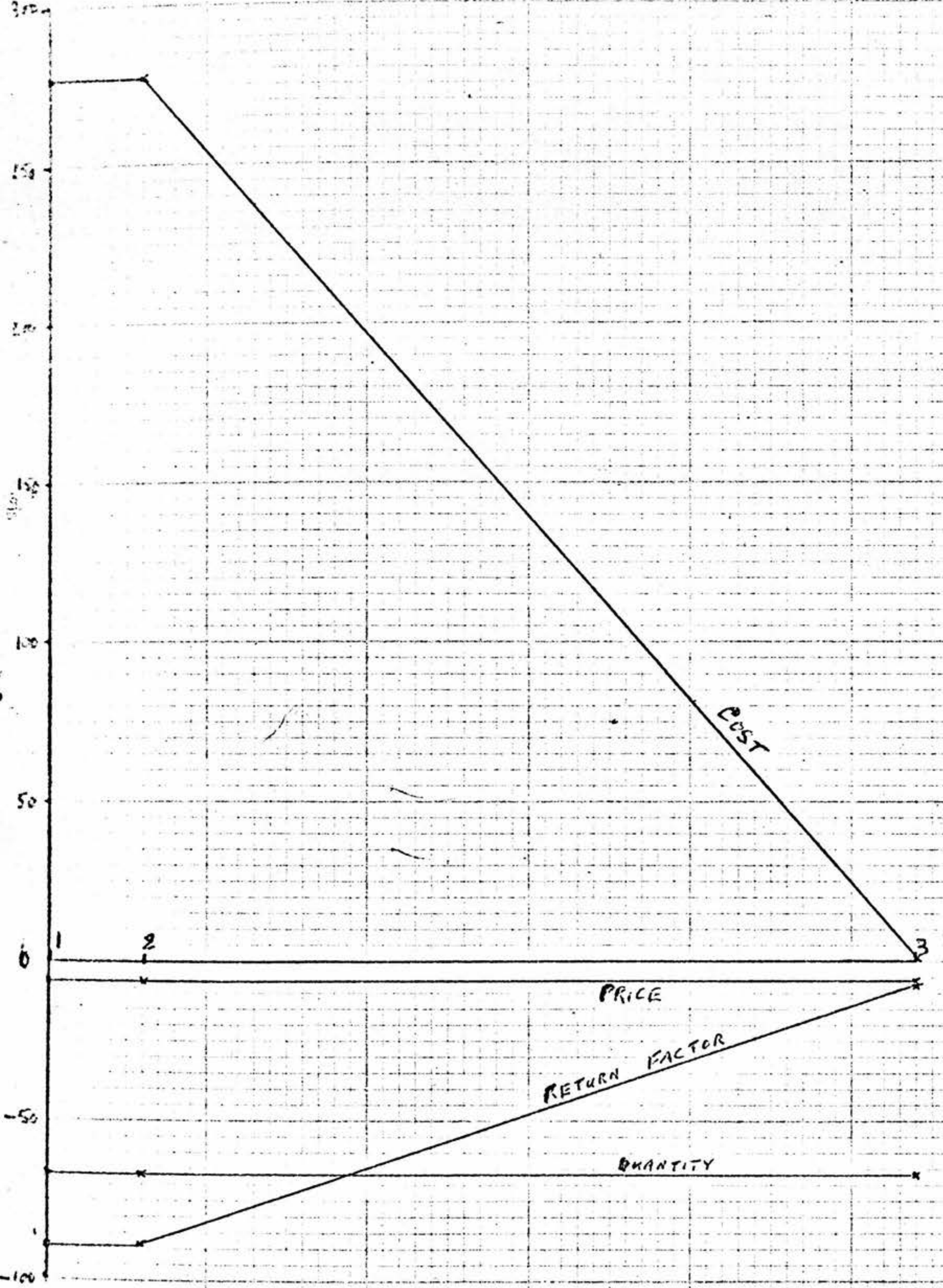


PROJECT 9A

GRAPH OF I AGAINST TIME



PROJECTION 10A :- GRAPH OF I AGAINST TIME



Project 1A Values of I (%ages)

Times During Development Period	Development Cost	Price	Quantity Sold	Return Factor
1	176.4	22.5	4.3	-12.5
2	80.0	22.5	-54.5	-57.3
3	81.4	22.5	0.0	-6.7
4	75.9	11.4	100.0	-55.7
5	36.2	9.1	100.0	-45.3
6	-	0.0	100.0	-31.4

NOTE - the last period is the end of the development period, uncertainty still remains about quantity sold and final return but not about price and development cost.

Project 2A Values of I (%ages)

Times During Development Period	Cost	Price	Quantity Sold	Return Factor
1	173.9	51.1	100.0	64.3
2	173.9	51.1	-36.3	-47.7
3	72.4	51.1	40.0	81.6
4	67.7	51.1	-30.0	-6.8
5	23.9	21.4	-30.0	+3.0
6	0.0	0.0	-30.0	+25.4

Project 3A Values of I (%ages)

Times During Development Period	Cost	Price	Quantity Sold	Return Factor
1	172.1	-13.3	71.4	0.0
2	172.1	-13.3	-45.4	-68.2
3	72.6	-13.3	20.0	10.5
4	72.6	-13.3	-40.0	-44.7
5	31.0	-13.3	-40.0	-27.6
6	0.0	0.0	-40.0	10.5

Project 4A Values of I (%ages)

Times During development Period	Cost	Price	Quantity Sold	Return Factor
1	6.2	-20.0	-90.0	-86.4
2	19.4	-20.0	-90.0	-86.9
3	15.4	-20.0	-90.0	-86.9
4	10.3	-20.0	-70.0	-60.0
5	0.0	0.0	-70.0	-46.0

Project 5A Values of I (%ages)

Time During Development Period	Cost	Price	Quantity Sold	Return Factor
1	-64.2	-16.7	8.3	+32.6
2	-48.8	-16.7	8.3	+32.6
3	0.0	0.0	8.3	-18.7

Project 6A Values of I (%ages)

Times During Development Period	Cost	Price	Quantity Sold	Return Factor
1	265.9	242.9	-45.4	-4.0
2	81.7	66.7	-40.0	2.1
3	41.9	66.7	-40.0	29.7
4	41.9	20.0	-40.0	-2.0
5	19.9	0.0	-20.0	54.8
6	17.8	0.0	-20.0	57.4
7	17.8	0.0	-20.0	33.3
8	29.9	0.0	-20.0	33.3
9	0.0	0.0	-20.0	33.3

Project 7A Values of I (%ages)

Times During Development Period	Cost	Price	Quantity Sold	Return Factor
1	15.8	56.7	-62.5	-47.6
2	15.0	56.7	-70.0	-54.2
3	10.3	56.7	-70.0	-50.0
4	-22.8	34.3	-70.0	-50.0
5	-29.5	34.3	-80.0	-71.1
6	0.0	34.3	-80.0	-71.1

Project 8A Values of I (%ages)

Times During Development Period	Cost	Price	Quantity Sold	Return Factor
1	53.1	-44.4	-90.0	-95.0
2	53.1	-44.4	-90.0	-95.0
3	27.3	0.0	-91.7	-91.1
4	0.0	0.0	-93.8	-91.8

Project 9A Values of I (%ages)

Times During Development Period	Cost	Price	Quantity Sold	Return Factor
1	153.7	-42.9	-68.8	-91.0
2	0.0	0.0	-37.5	-18.2

Project 10A Values of I (%ages)

Times During Development Period	Cost	Price	Quantity Sold	Return Factor
1	276.7	-6.0	-66.7	-87.9
2	276.7	-6.0	-66.7	-87.9
3	0.0	-6.0	-66.7	-7.0

The main conclusions that can be drawn from the preceeding analysis of forecast behaviour are as follows. First, cost forecasts or predictions certainly get closer to the true value over time. However, in most cases cost forecasts converge on the true value slowly and it requires about 50% of the development period* before the bias in the forecast becomes small enough for us to say the uncertainty in our cost estimate has been satisfactorily resolved. Second, estimates of price are sufficiently close to the final value in most cases, with the important exception of project 6. With project 6, a technically advanced product, it is clear that there is a large measure of uncertainty in the initial price forecasts. However, we can see that by period 4 the uncertainty in the price forecast is reduced to only 20% This can be explained by the great improvement in the cost forecasts over the first four periods and the firm's cost-plus pricing policy.

Third, in most cases, estimates of sales** tend to oscillate widely about the true value. This finding reflects the great degree of uncertainty that is faced by engineers and marketing managers in estimating market conditions for a product generated as a by-product of the research and development output.

Fourth, if we analyse the behaviour of the return factor index, into which estimates of the above three factors are placed, we find predictably that uncertainty about the worth of the project is not resolved quickly through time because of the degrees of uncertainty

---

* Actual times for projects are not given here for confidentiality reasons. Although forecasts are not made at equal intervals of time during the development period it is reasonable to consider the middle forecast as being made approximately half way through a given project.

** Since the electronics industry is competitive in nature, we would expect that a firm would know price i.e. be a price taker but be uncertain about demand. In a monopolistic situation we would expect uncertainty about both price and demand.

inherent in cost and sales forecasts.

We have looked in general terms at the behaviour of the individual forecasts. Now, we must consider a number of general issues on which this study provides guidelines. We should note immediately that the evidence here leads us to infer that uncertainty about project outcome, sales and cost remains until a significantly large proportion of the development period has elapsed. This is an important inference because it suggests that a parallel path strategy for a firm such as A carrying out applied, product orientated R & D work is a costly proposition. The mere fact that uncertainty is only slowly resolved implies that learning by doing on projects will be costly and produce high project wastage rates.

Another equally important point is that the greatest degrees of uncertainty are evidenced in cost and sales forecasts. How can we improve these forecasts? The next chapter considers the extent to which we can use previous estimating experience to revise present or future experience but it is important to state here that we should try to extract from past data, however rough they may be, lessons from which future estimating practice can be developed and improved. An additional source of improvement would be to educate the engineer and manager more about the characteristics and nature of the R & D process and, in particular, about the close interactions between economic and technical factors on a project.

Cost and sales as we have seen are the areas of great forecast uncertainty. However, we should ask how much the area of uncertainty is clouded by the uncertain technical or design nature of the project. In particular, is there a correlation between changes in the objectives of projects and inaccurate forecasting behaviour. Unfortunately in this study our sample of projects is so small that on only one project was there any significant change in project objectives. The project on which this occurred was project 6A and we have noted already the huge improvement in the cost and price forecasts that occurred in the 4th period of the development stage of 6A. Instrument 6A, which is a specialised testing instrument, had a change in performance and design specifications between the third and the fourth period. The changes were caused by a number of factors including greater technical awareness and the need for certain features to be added to the original design in order to improve the instrument's performance in a number of areas of application. Discussions with project engineers suggest that if these changes in objectives, had been known initially the initial estimate of cost would have increased by no more than 50% which would have had the effect of reducing the forecast inaccuracy for cost as a whole by no more than 15%. The engineers felt that lack of knowledge of the final design configuration was not sufficient on its own to explain the extent of forecast inaccuracy. They mentioned factors like technical uncertainty and the lack of appreciation of how long it would take to complete development work as being equally important.

We have not attempted here to break down the values of I either by degree of technical advance or commercial success. There are two reasons for this: first, the analysis would tend to be repetitive given the breakdown presented earlier and second, the analysis can be carried out simply enough from observation of the graphs by the reader. The important point in this section is that we provide evidence on forecast behaviour which is not available elsewhere in great detail and this enables us to conclude that uncertainty resolution on the R & D projects studied here is generally a slow process. As a result a learning by doing or a parallel path R & D strategy might prove to much less useful in industrial R & D than military R & D contract work.

7.3.3. Validity of the Return Factor Index as a Measure of Project Worth

Firm A uses a formal selection index, basically a ratio of the form Net Revenue/Cost, to evaluate the worth of research project. Ratios like firm A's index require estimates of cost of development, and sales and revenue variables which we have already seen to be very inaccurate in most cases. Such large inaccuracies in the estimates of cost and sales factors can make the measure of worth of a project relatively useless.

There is, of course, a further more important question to discuss when considering the validity of a measure of worth such as a return factor, namely: how sure are we that the Net Revenue/Cost ratio is an adequate measure for evaluating the worth of an investment project such as a research and development project? Should projects be evaluated solely in terms of financial criteria?

In the analysis we shall first consider the inaccuracy in the initial return factor prediction in terms of its closeness to the final return factor. We then consider what other financial criteria would be more useful in analysing the worth of research projects and, in particular, criteria based on the actuarial principle of discounting cash flows. The discussion of alternative criteria is illustrated by cash flow diagrams for the ten projects already considered in firm A.

If we now consider Table VI we find our usual analysis of F factors i. e. final values initial estimated values for the return factor indices.

Table VI

F RATIOS OF FINAL RETURN FACTOR VALUES TO INITIAL RETURN FACTOR ESTIMATES

Project	F. Ratios	
1	0.88	
2	1.64	
3	1.00	Mean F Ratio for Technically Advanced Projects = 1.12
4	0.14	
5	1.35	Mean F Ratio for Non-Technically Advanced Projects = 0.33
6	0.96	
7	0.24	
8	0.01	
9	0.11	
10	0.12	

It would appear from the table that return factor predictions are better for technically advanced than for less technically advanced projects. This is more by accident than design since if we refer back to the behaviour of sales and cost forecasts through time for the technically advanced projects we find that in most cases changes in cost forecasts are associated with compensating changes in sales forecasts either instantaneously or a number of periods later. The net effect of these changes on the project return factor index is to leave the value of the return factor at the end of the project's life approximately the same as it was initially. This can also be explained in a different way by referring back to Table II. In that table we found that the mean F ratios for cost, quantity sold and price for more and less technically advanced projects were 2.97, 1.58 and 1.75 and 1.78, 0.31 and 0.95 respectively. If we now remember that a return factor ratio is of the form Net Revenue/Cost, final ratios as compared with initial ratios for technically advanced projects will be about the same because the increase in the denominator, cost, is met by corresponding increases in the numerator, revenue, which is proportional to price times quantity sold. Similarly, for less technically advanced projects cost escalates i.e. the denominator increases in size relative to the numerator which decreases because of the reduction in sales forecasts. The net effect is, therefore, to reduce the value of the return factor.

We can see, therefore, that return factor predictions are affected by the weaknesses inherent in the input forecasts of sales and cost. Because sales and cost forecast inaccuracies tend to cancel out in the case of technically advanced projects but not in the case of less advanced projects the difference in the research team's ability to forecast return can be explained. It is clear, therefore, that the validity and usefulness of the return factor index is severely weakened by problems in the forecasts of sales and costs. This suggests that improvements in the methods of assessing and presenting forecasts must be made to the extent that initial estimates are assessed as range rather than point forecasts i. e. we take the uncertainty in the forecast into account by specifying the range within which it is likely to occur rather than the exact point of occurrence.

Any return index is thus dependent upon the accuracy and method of presentation of forecast variables. Its validity is also dependent upon the extent to which it represents the financial operations of the firm. There has been a great deal of adoption in recent years of techniques for financial appraisal which take full account of the time value of money. Such discounting techniques are based upon the inverse of the actuary's principle of compound interest. The attraction of the techniques for the manager of the firm is that they take full account of the distribution through time of the cash flows accruing to investment and earnings. They clearly differ from the type of return factor index of Firm A which is a a ratio of Revenues to Costs and where revenues are treated as being of the same worth to the firm even if they occur predominantly towards the end of a projects life. A discounting criterion would weight revenues and costs, if necessary, by the interest rate factor which reflects the time value of money.

In Table VII below we present ratios of the net present value of projects 1-10 to their initial cost. The net present value (NPV) criterion has been obtained by discounting each project's gross cost and revenue cash flows (see the cash flow graphs for each project presented on subsequent pages) by the appropriate cost of capital or discount rate for the firm and obtaining the net present value by treating discounted revenues as positive quantities and discounted costs as negative quantities. If the firm has only finite amounts of money available for investment in R &D projects, it is reasonable to consider NPV per unit of money employed i. e. cost as a measure of worth of an individual research project.

Table VII

RATIOS OF NET PRESENT VALUE TO INITIAL COST FOR TEN PROJECTS IN FIRM A

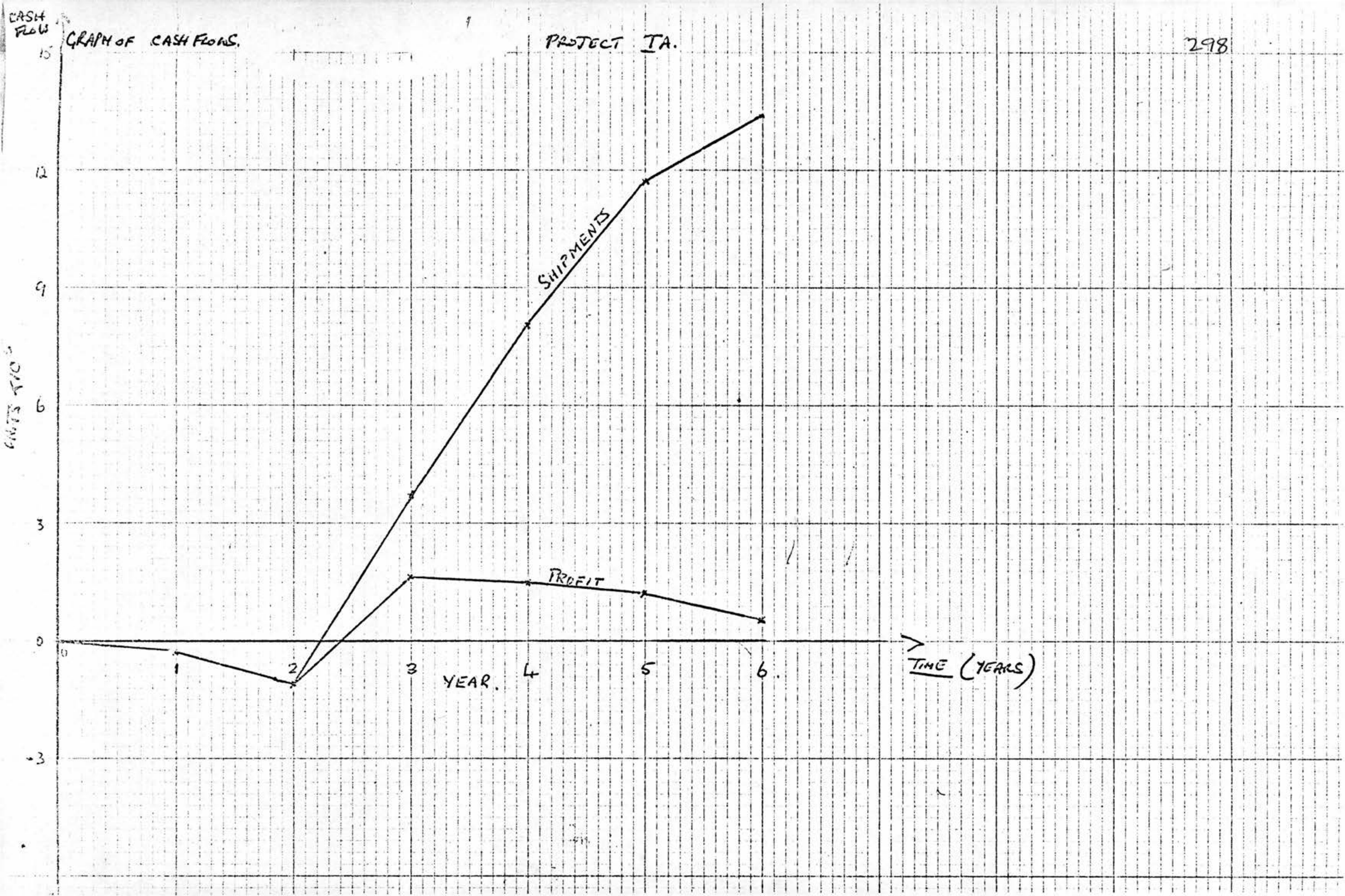
Projects	Ratio (NPV) Cost	Ranking of Projects in Terms of NPV/Cost	Ranking of Projects in Terms of final R. F.	Ranking of Projects in Terms of initial R. F.
1	1.48	6	6	9
2	2.78	1	1	7=
3	1.25	7	4	7
4	2.15	3	7	2
5	2.45	2	2	6
6	1.60	5	3	5
7	0.06	8	9	10
8	-0.71	10	10	3
9	+0.03	9	8	4
10	+1.75	4	5	1

Colums 3, 4 and 5 of this table show a ranking of each project in terms of its worth to the firm under the NPV/Cost, final return factor and initial return factor criteria respectively. No meaning should be read into this ranking about selection between projects because these projects occurred in the period 1963-69 at random intervals. The ranking is merely undertaken to show that different criteria assess the worth of projects differentially and result in return factor or worth predictions that do not imply the same decisions to adopt or select a project by the firm concerned.

It is clearly argued that predictions of final financial outcome of a project will improve with better forecasting of economic factors and adoption of financial discounting criteria of project worth. Financial outcome is not the sole criterion of worth of a project because of the need for the firm to develop its R & D expertise in several technical areas. However, if the engineer / manager better appreciates the interaction between technical and financial factors then the efficiency of project selection decisions is likely to show a significant improvement.

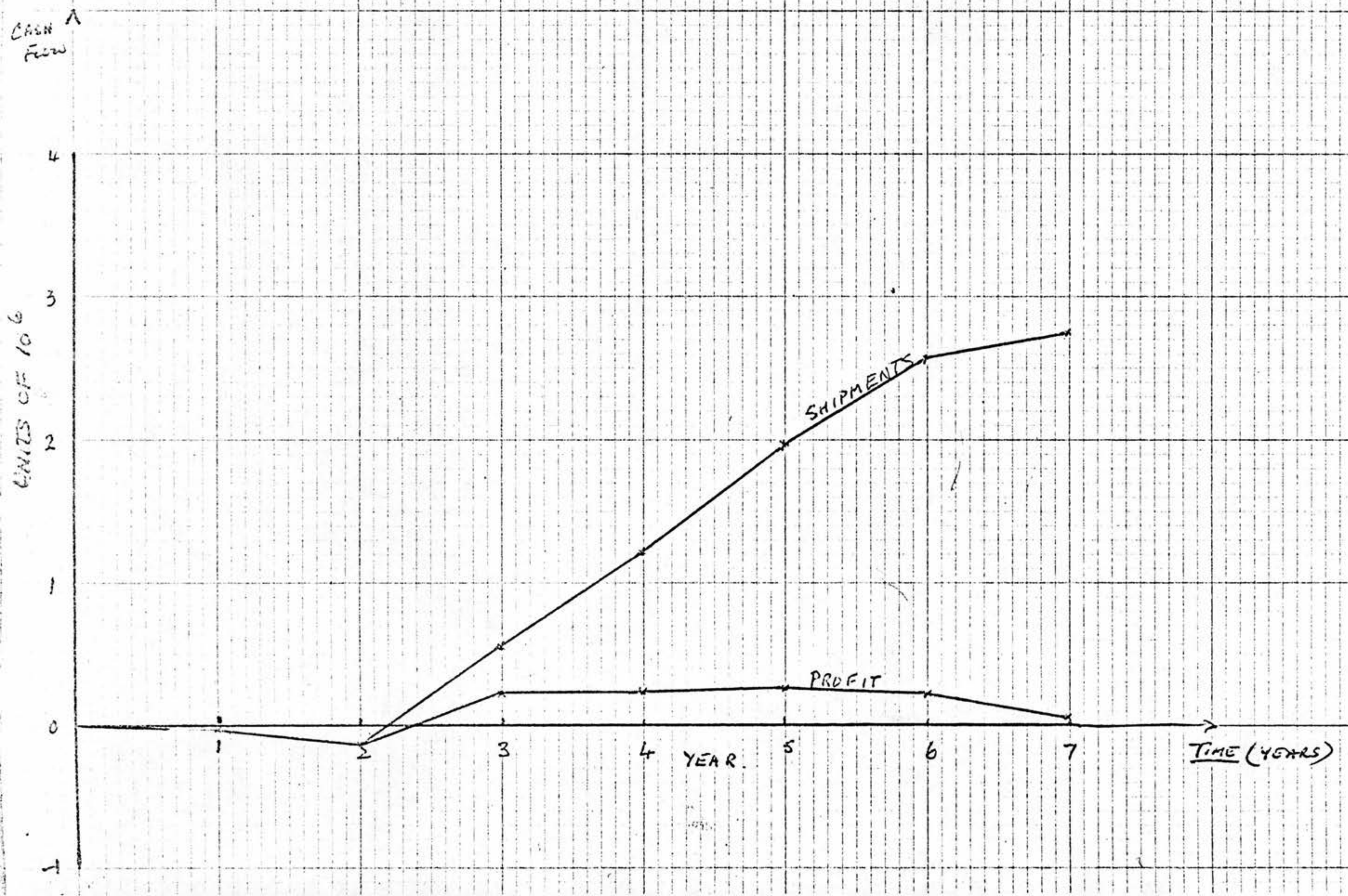
One way in which sales forecasting procedures may improve is through the observation of past actual sales data for R & D projects. In fact, if we consider the graphs of sales against time for the 10 R & D projects of firm A then only projects 1A, 2A, 3A, 4A, 5A and 6A show evidence of the product life cycle philosophy which is used in the commercial exploitation of any product it produces. Engineers typically state that

GRAPH OF CASH FLOWS. PROJECT IA.

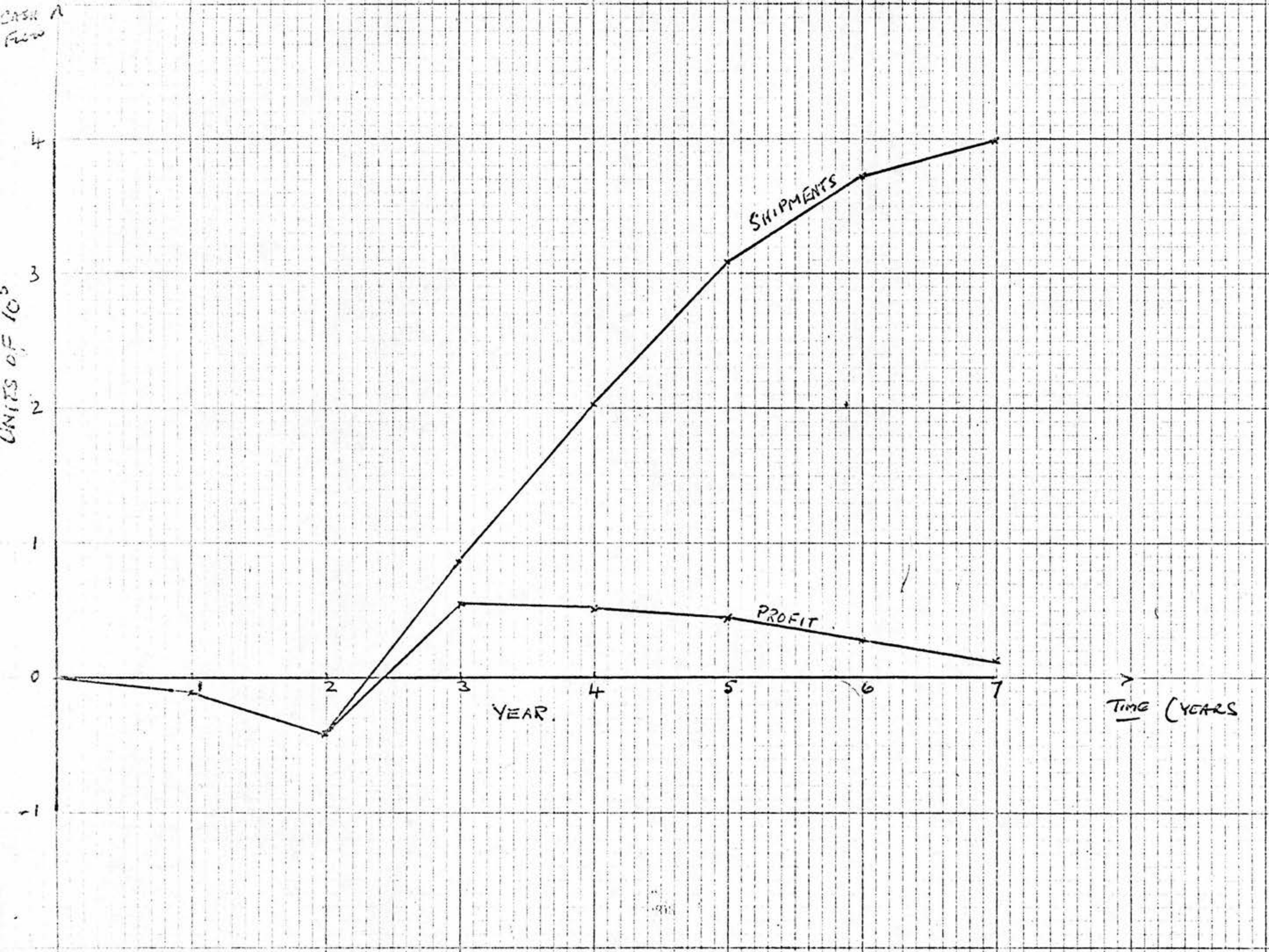


PROJECT 2A

CASH FLOW GRAPH.

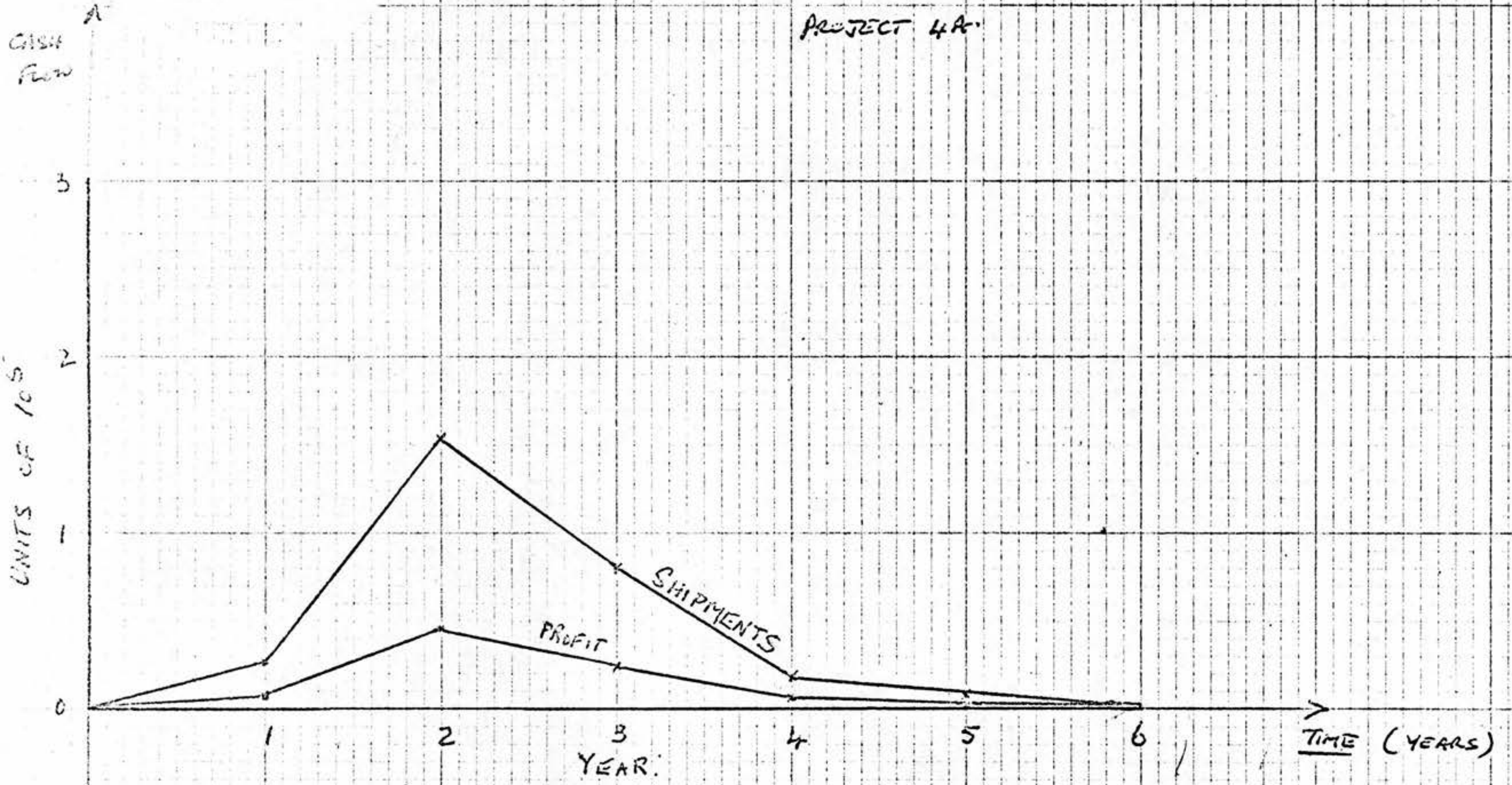


PROJECT 3A :- CASH FLOW GRAPH.

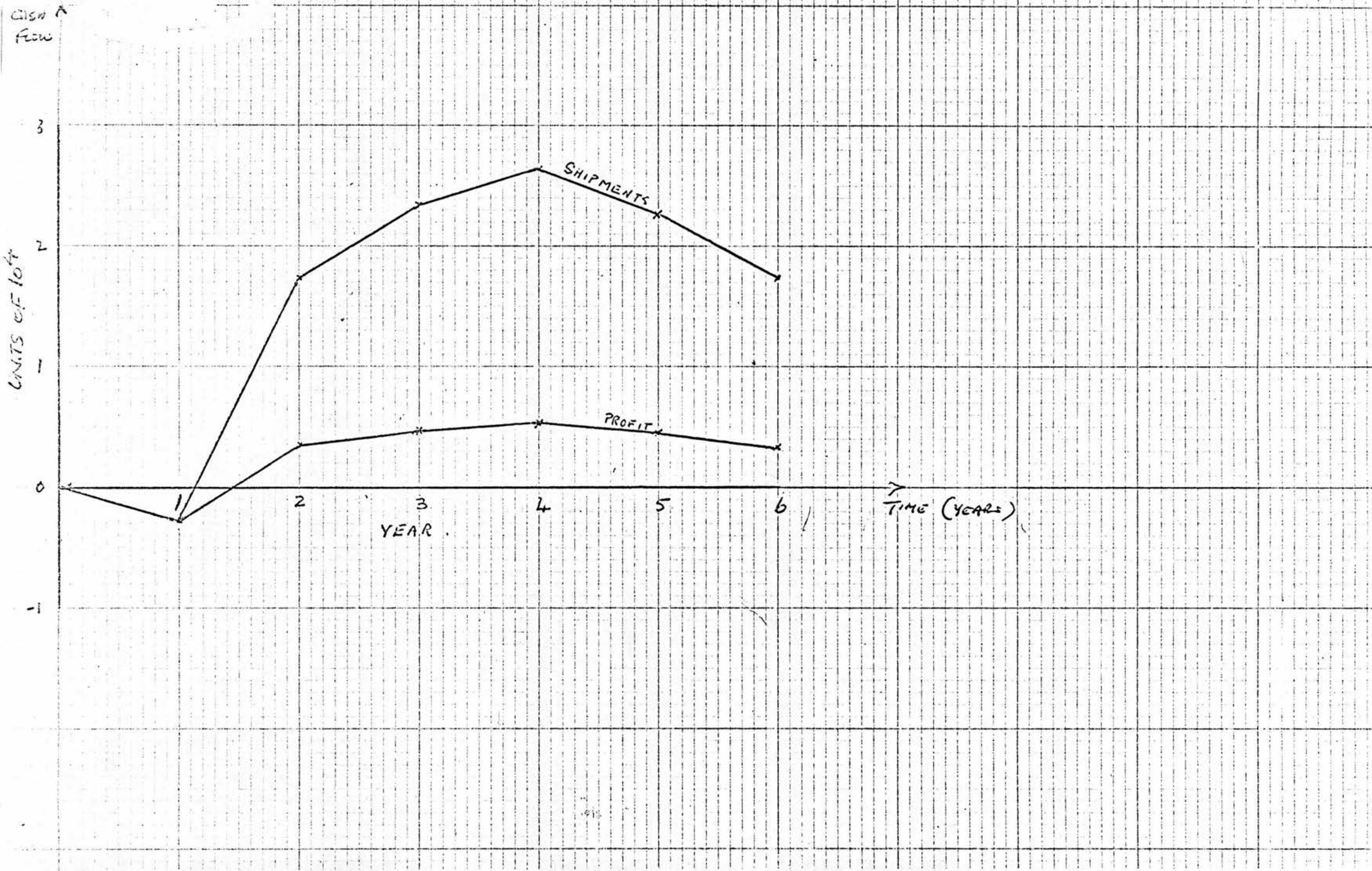


CASH FLOW DIAGRAM

PROJECT 4A.

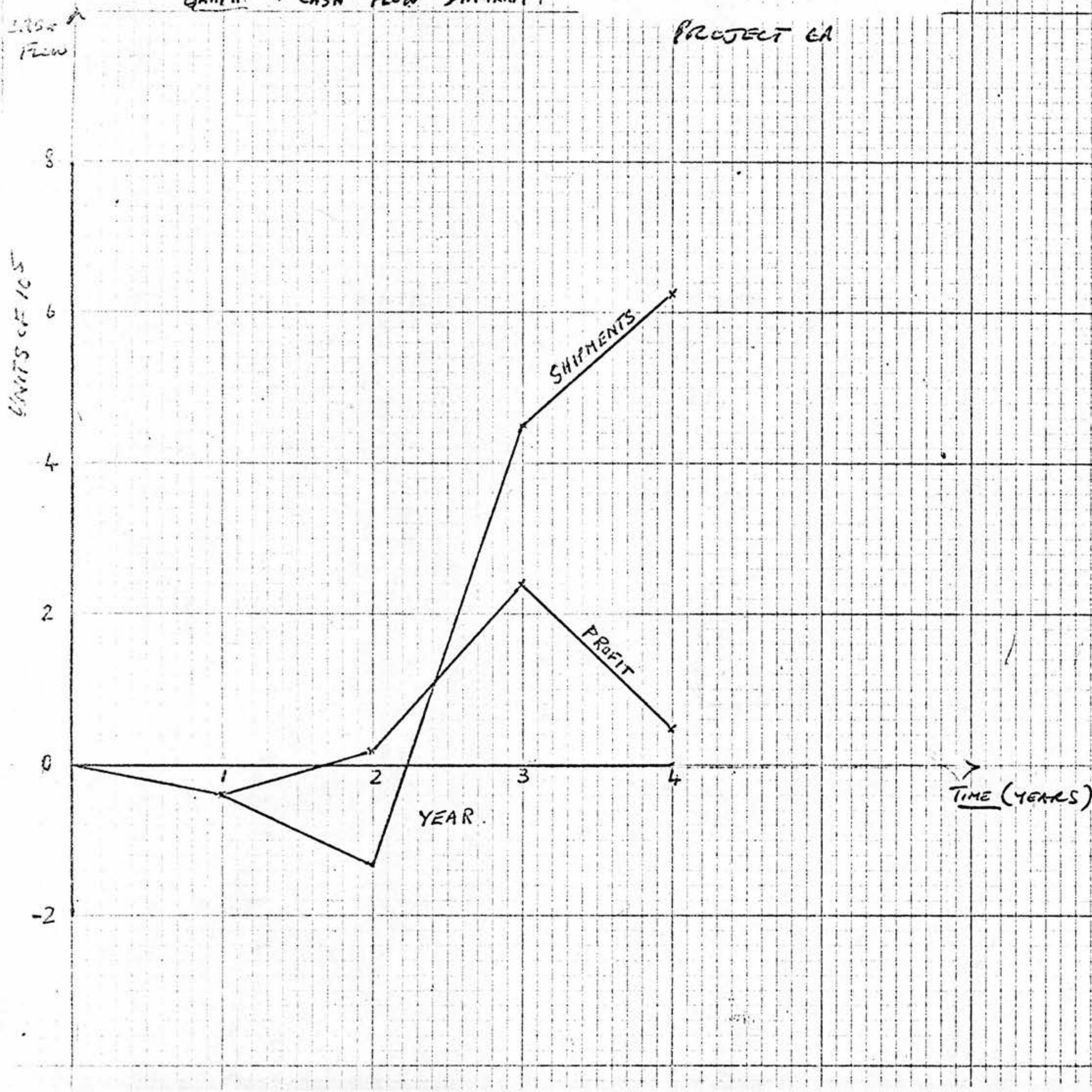


CASH FLOW DIAGRAM PROJECT 5A



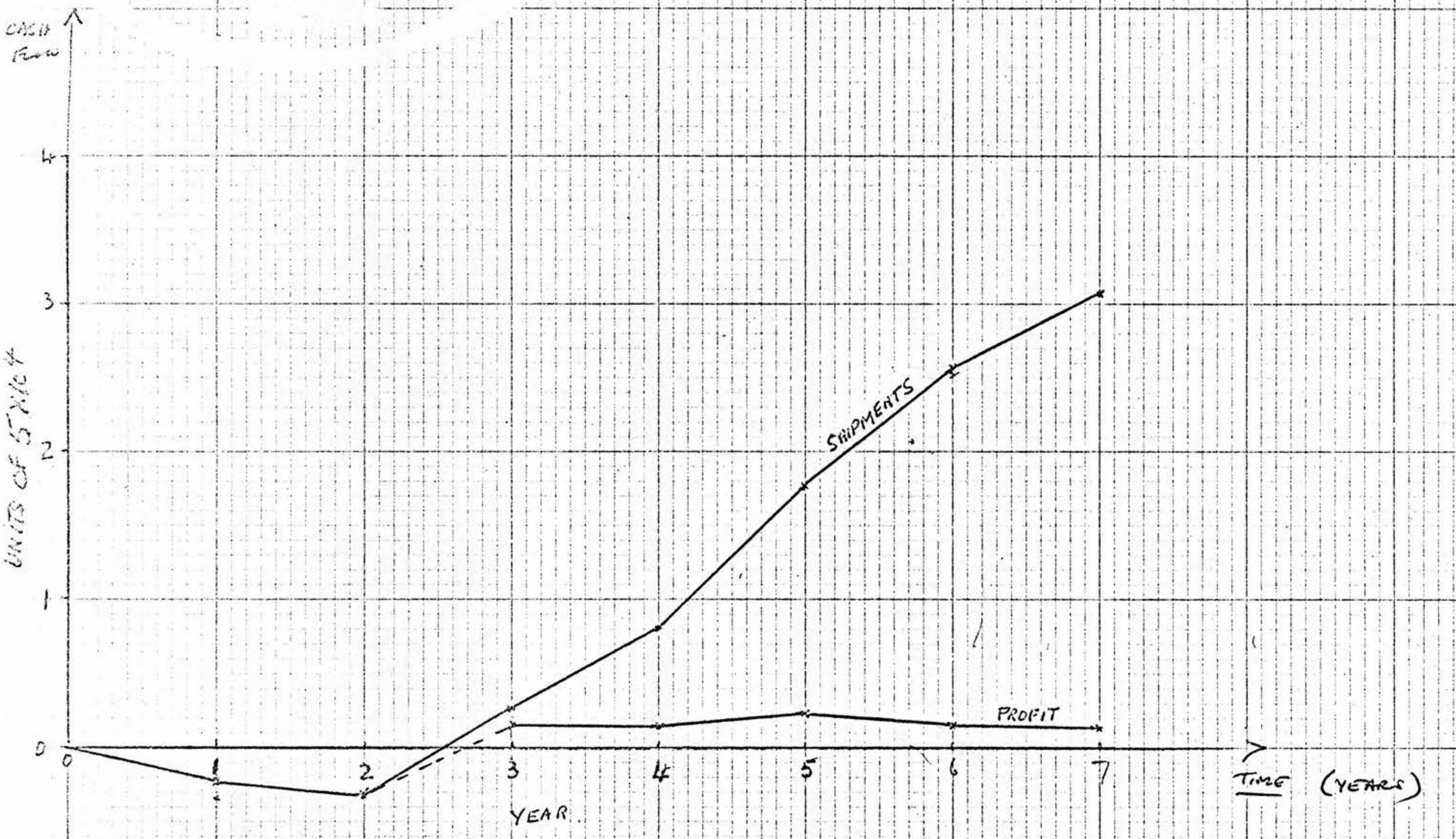
GRAPH - CASH FLOW DIAGRAM.

PROJECT CA



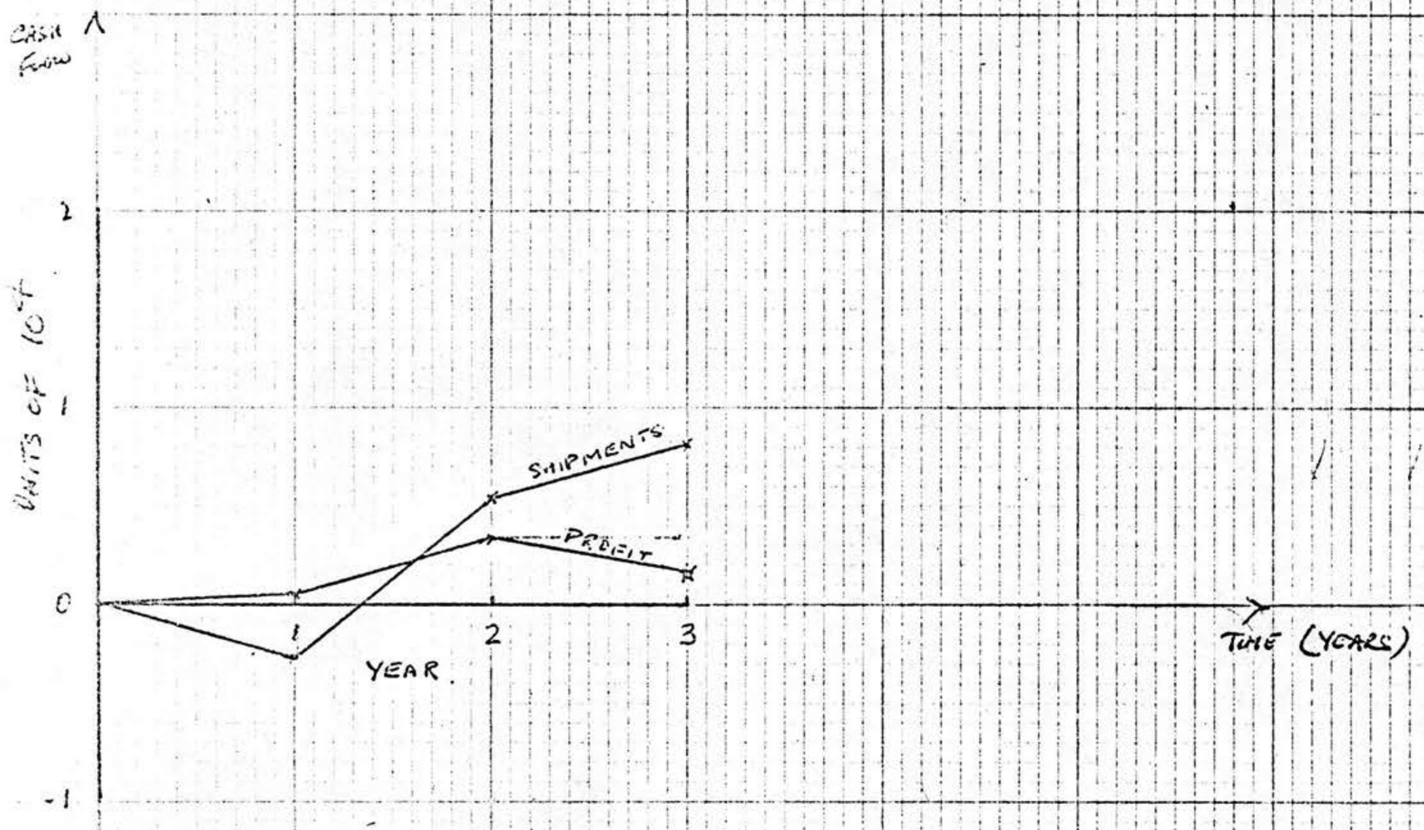
CASH FLOW DIAGRAM

PROJECT 7A

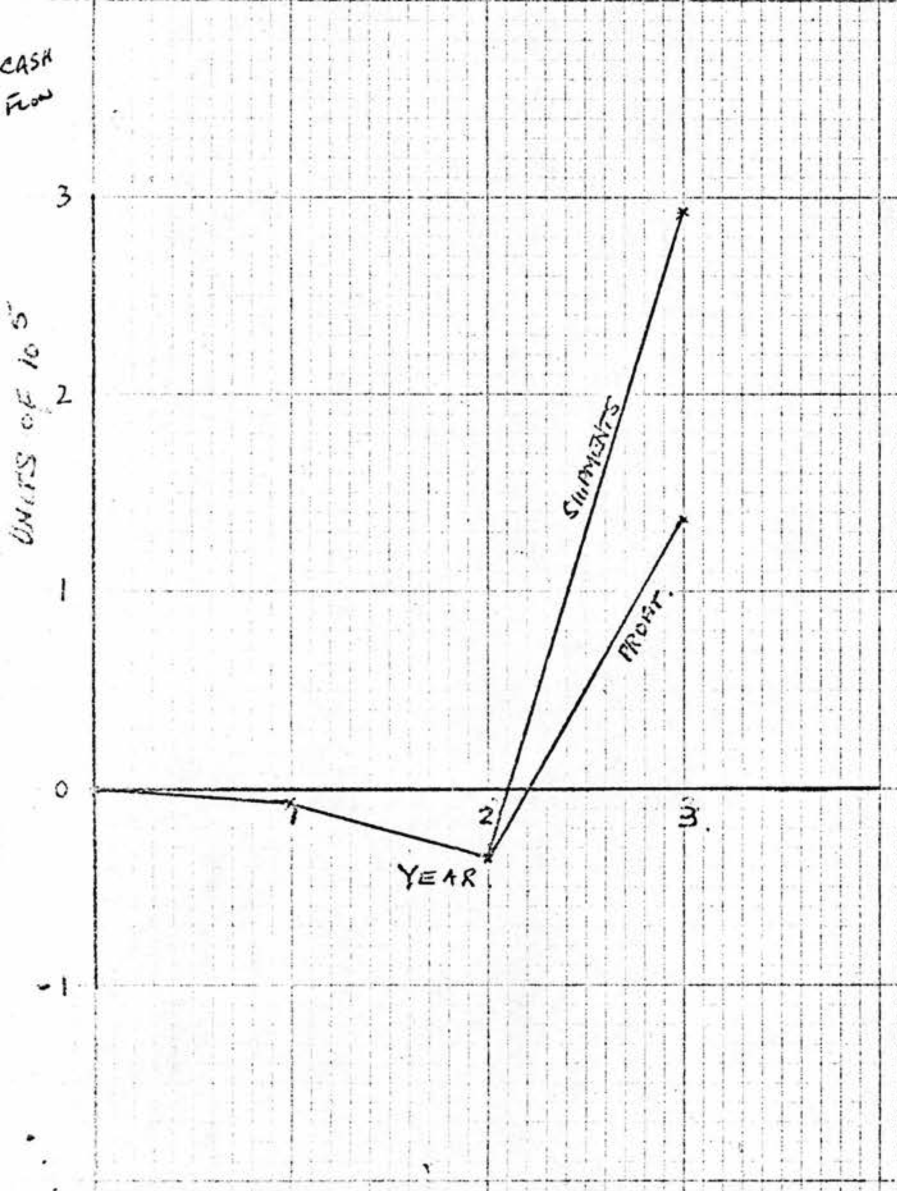


CASH FLOW DIAGRAM
PROJECT 8A

CASH FLOW DIAGRAM
PROJECT 9A.



CASH FLOW DIAGRAM PROJECT 10A.



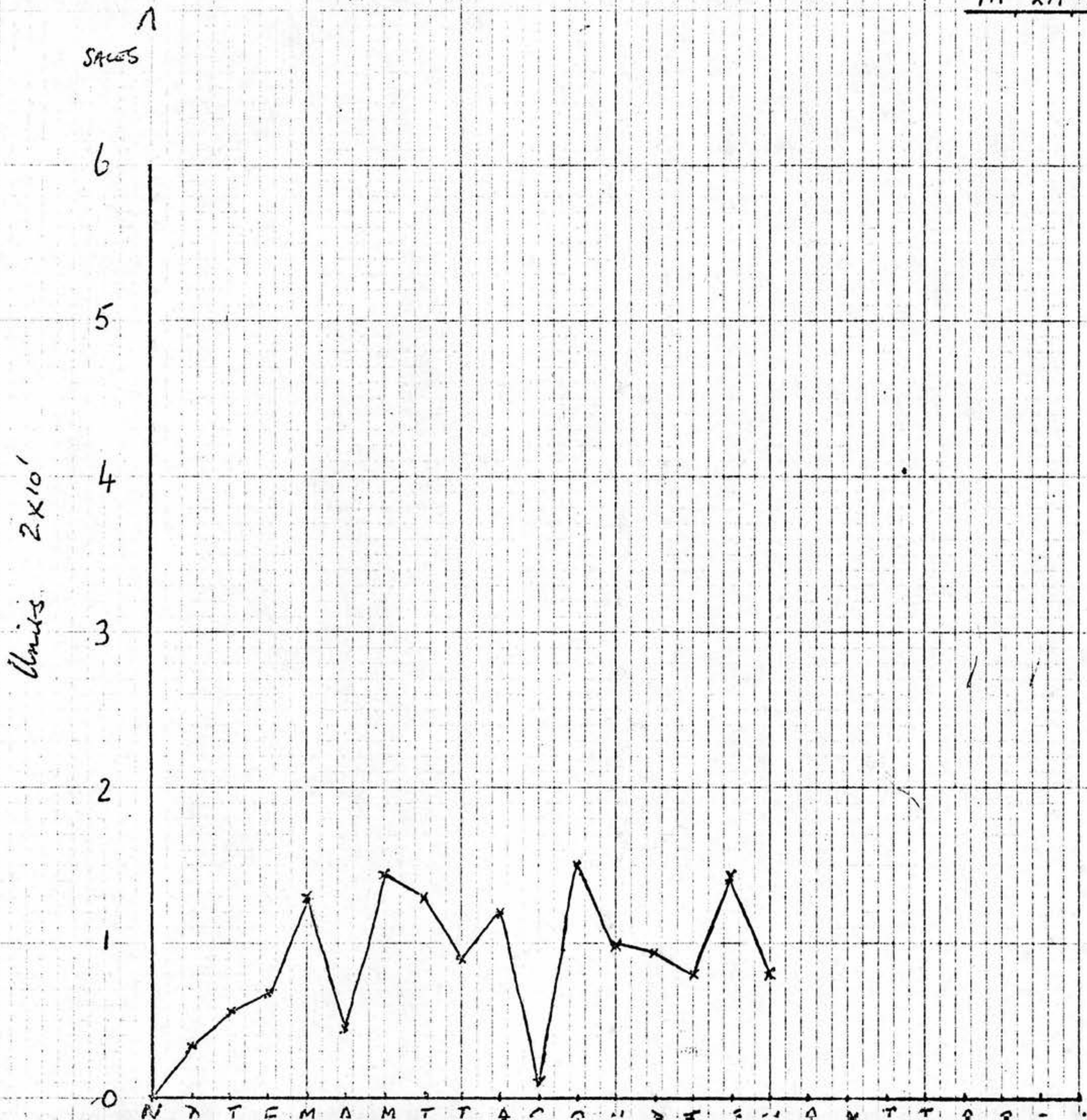
they estimate sales of a product by picturing an idealised product life cycle diagram showing growth, maturity and decline for the project, by estimating the peak or mature sales volume and then assigning sales to each phase of the project according to the product life cycle diagram. This is clearly an efficient procedure if we have a constant or known period of time for the project's life cycle diagram with unknown parameters to be estimated by the forecaster. As we have said only five of the projects show evidence of a product life cycle shape and it is significant that four of these are the technically advanced projects. This suggests, on the basis of somewhat limited evidence, that the concept is useful for, and applicable to, R & D projects of medium to large complexity. We can, however, make this statement slightly stronger by remembering that project 10 is a contract project and cannot be expected to generate sales according to a project life cycle curve. Thus, over 50% of the projects can be viewed in terms of a product life cycle but particularly those with a significant degree of technological innovation in design. Therefore, rigid adherence to sales forecasts made in terms of the product life cycle can only be justified with relatively technically advanced R & D projects.

7.4. Summary Statement on the Performance of the R & D Department in Firm A over the Period Studied

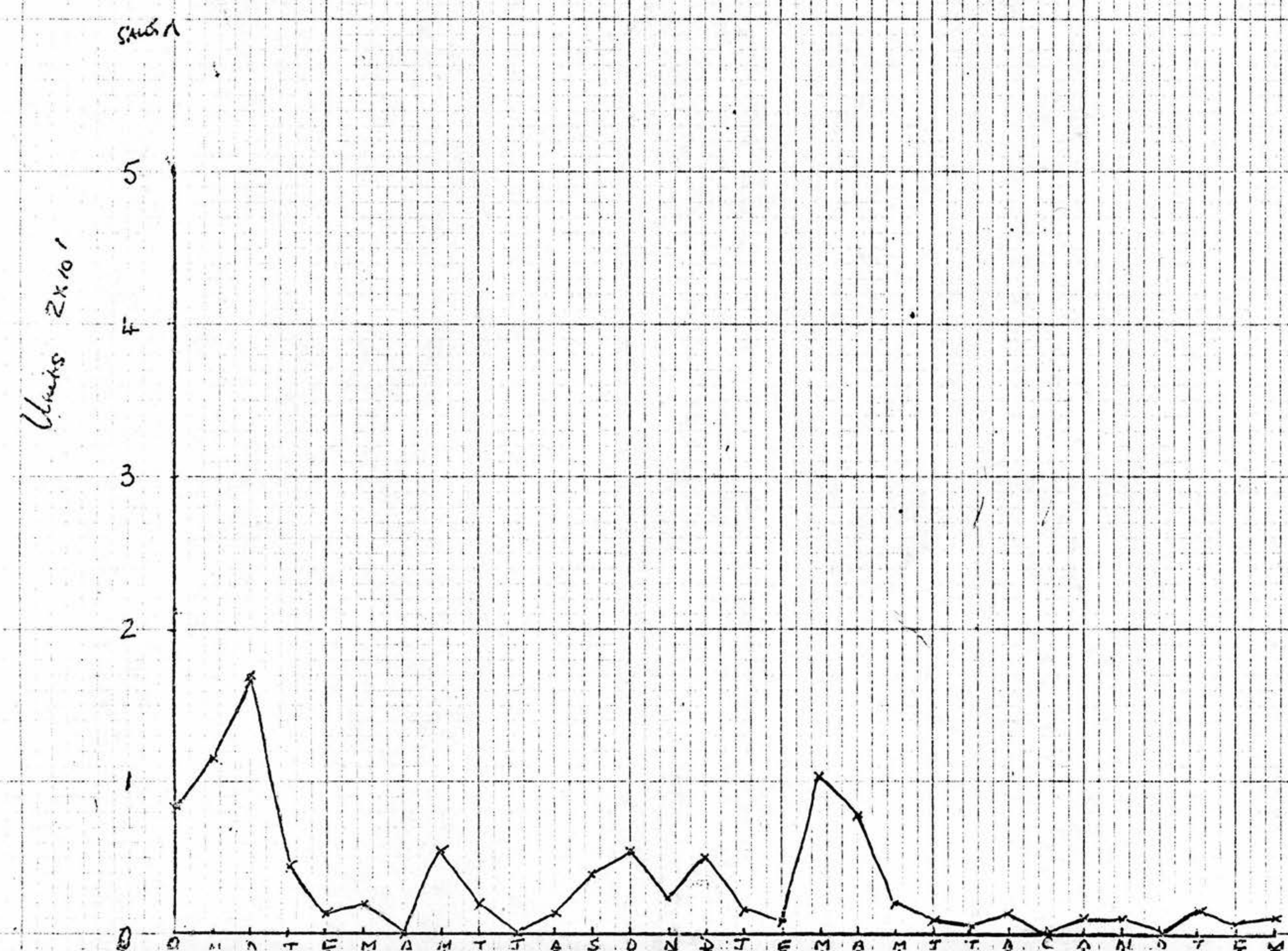
In this very short section we consider the global performance

SALES IN QUANTITIES

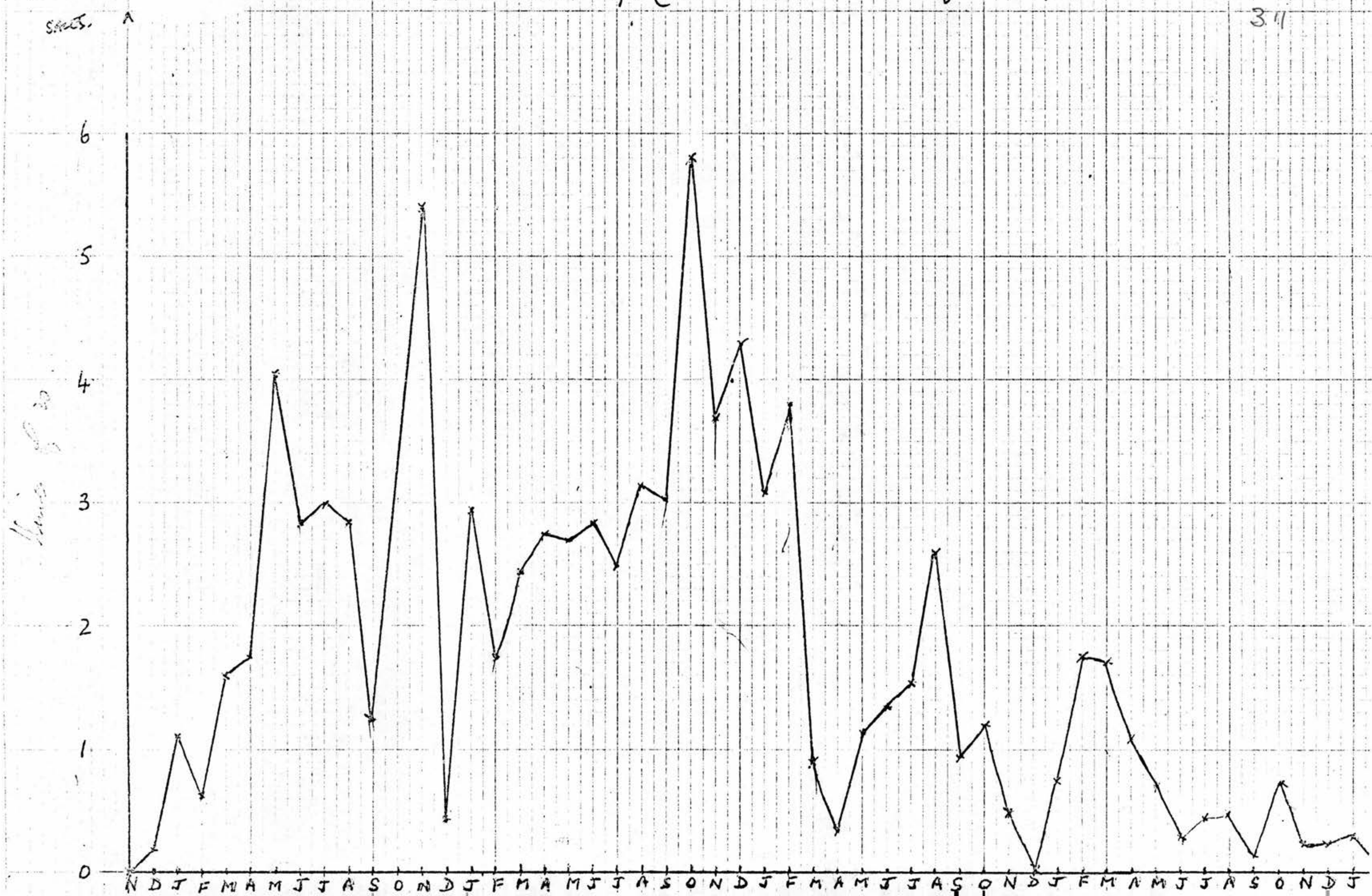
1A 2A 3A



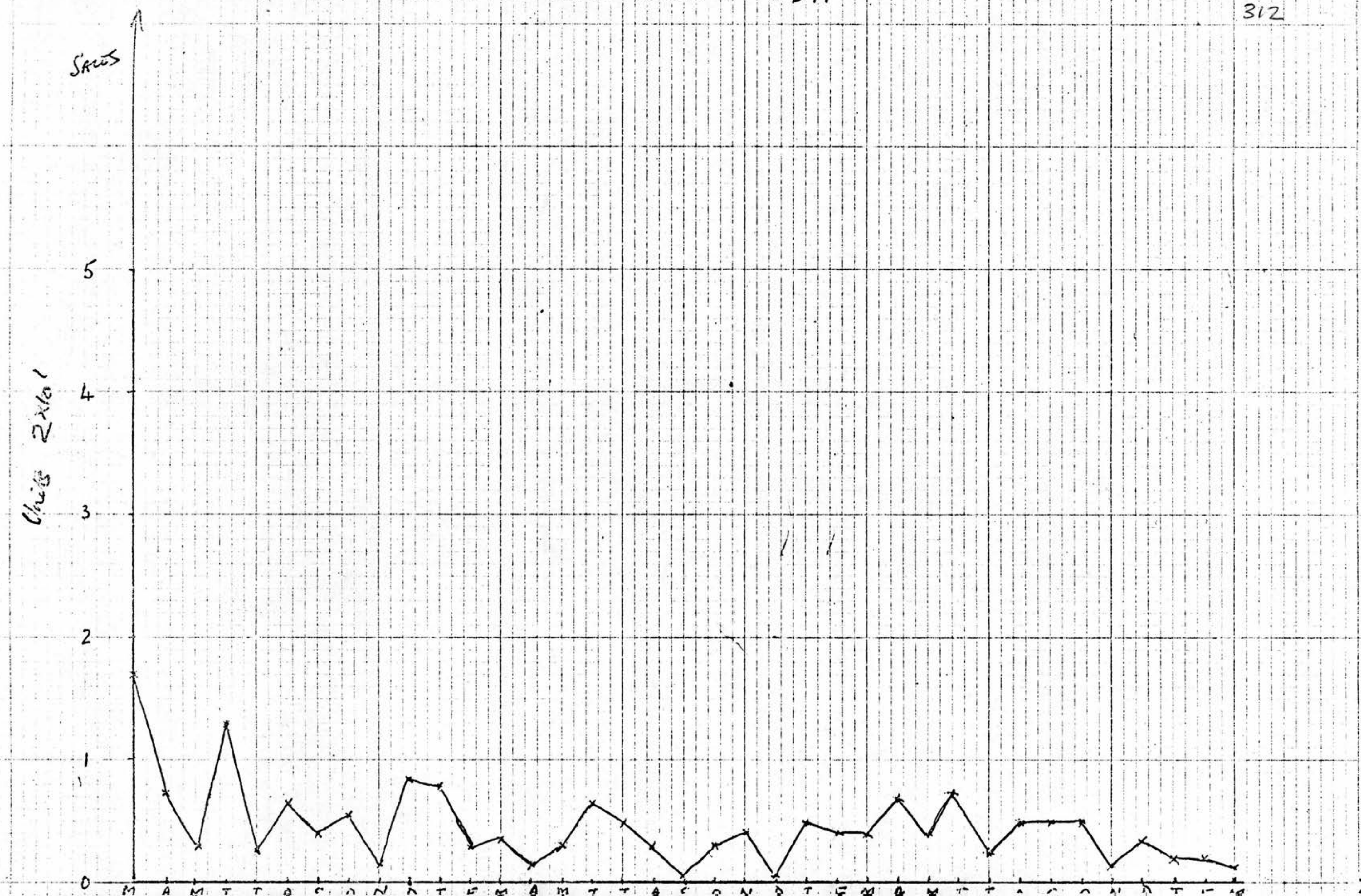
SALES IN QUANTITIES. - 4A. 310



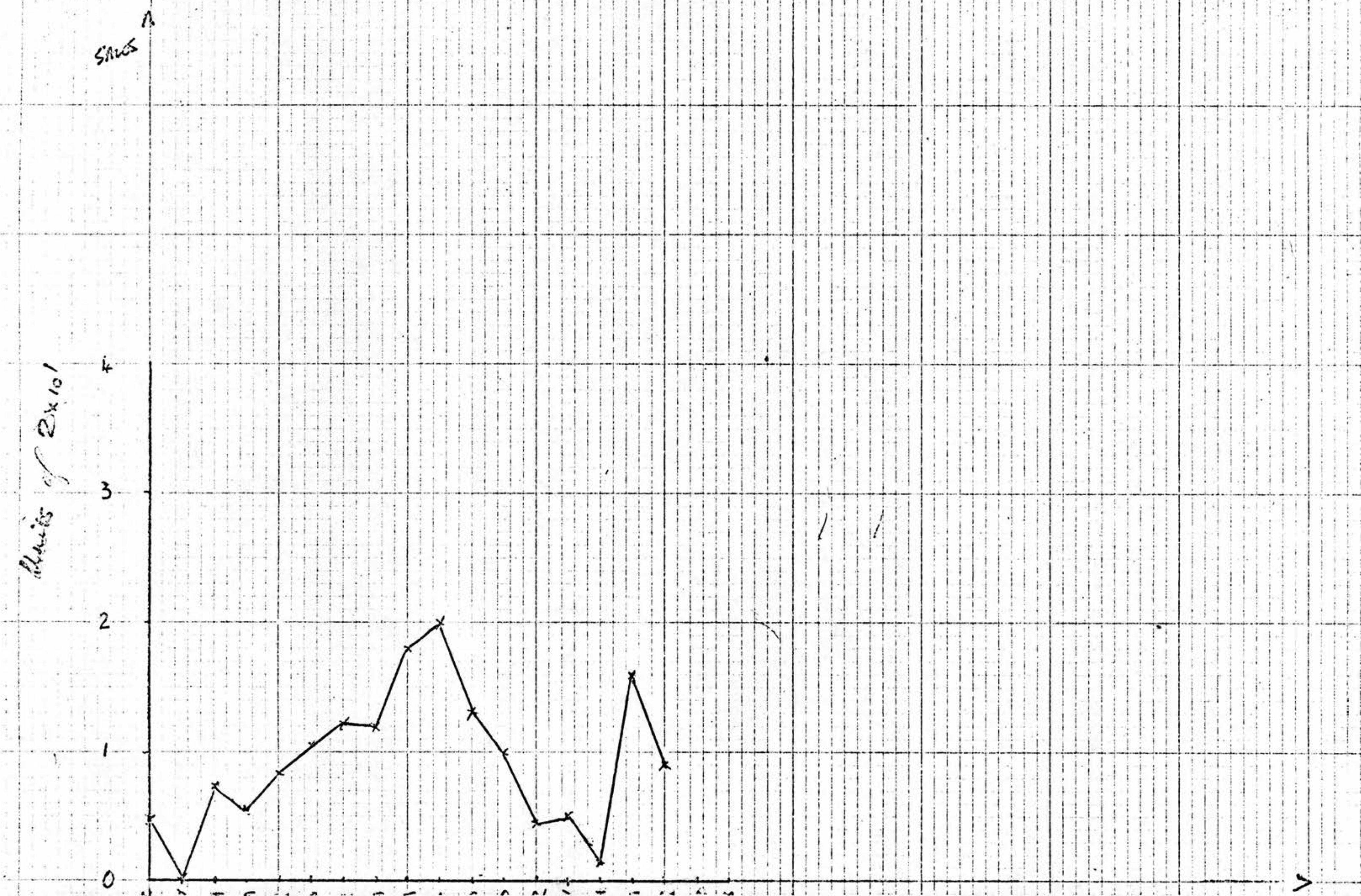
SALES IN QUANTITIES. 4A (an earlier instrument designed to perform similar functions)



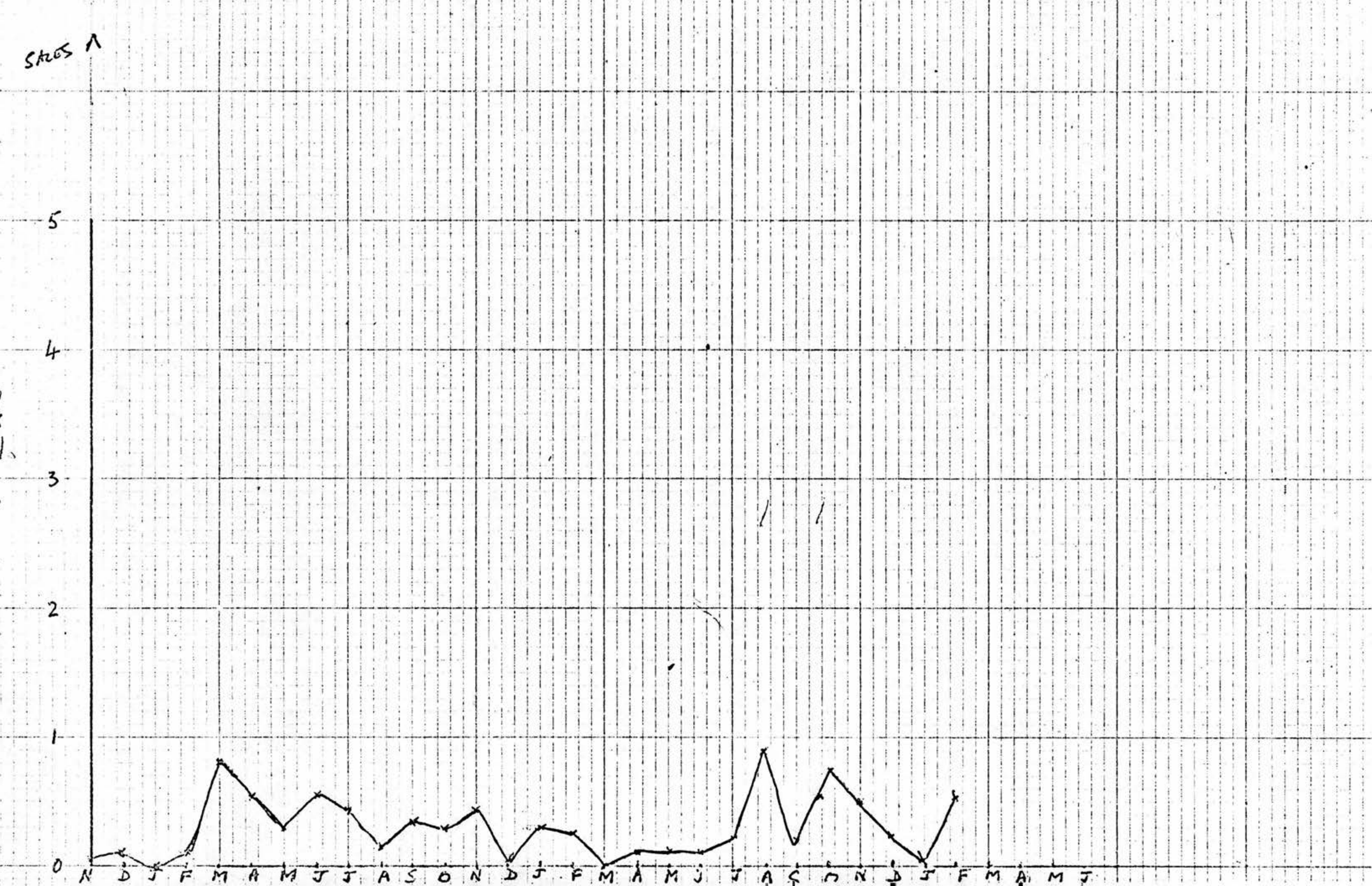
SALES IN QUANTITIES. – 5A.



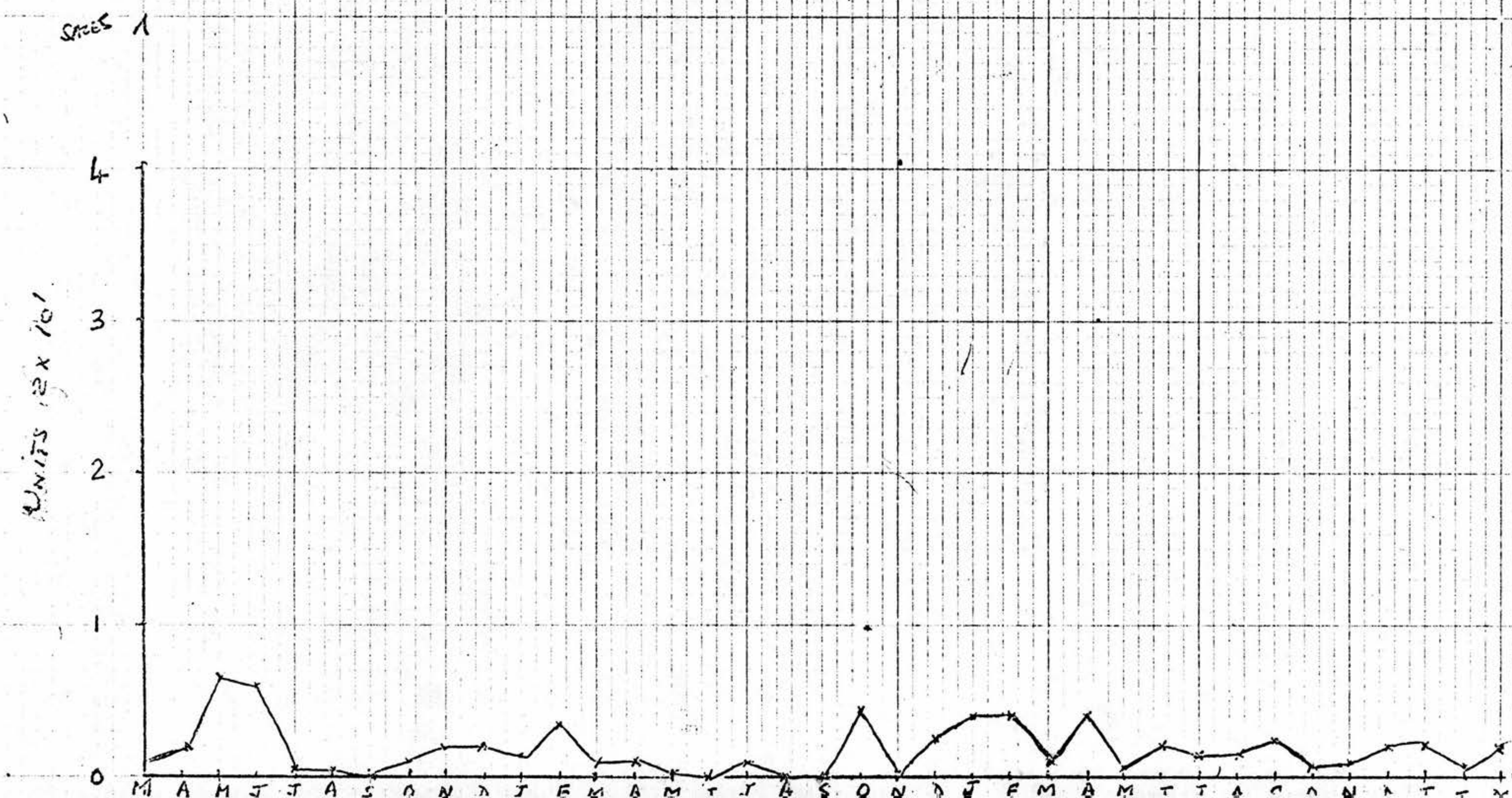
SALES IN QUANTITIES. 6A



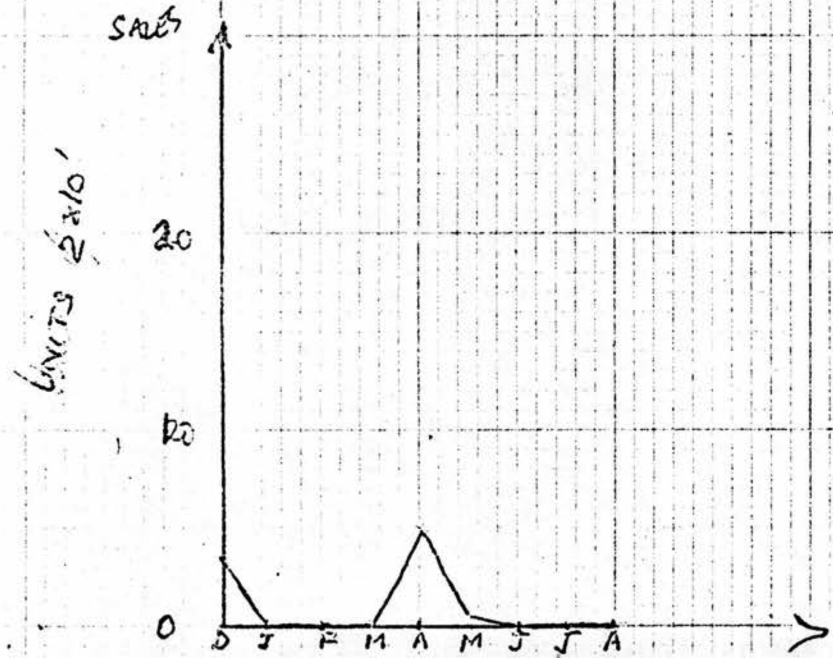
SALES IN QUANTITIES. 7A. (earlier similar type of instrument)



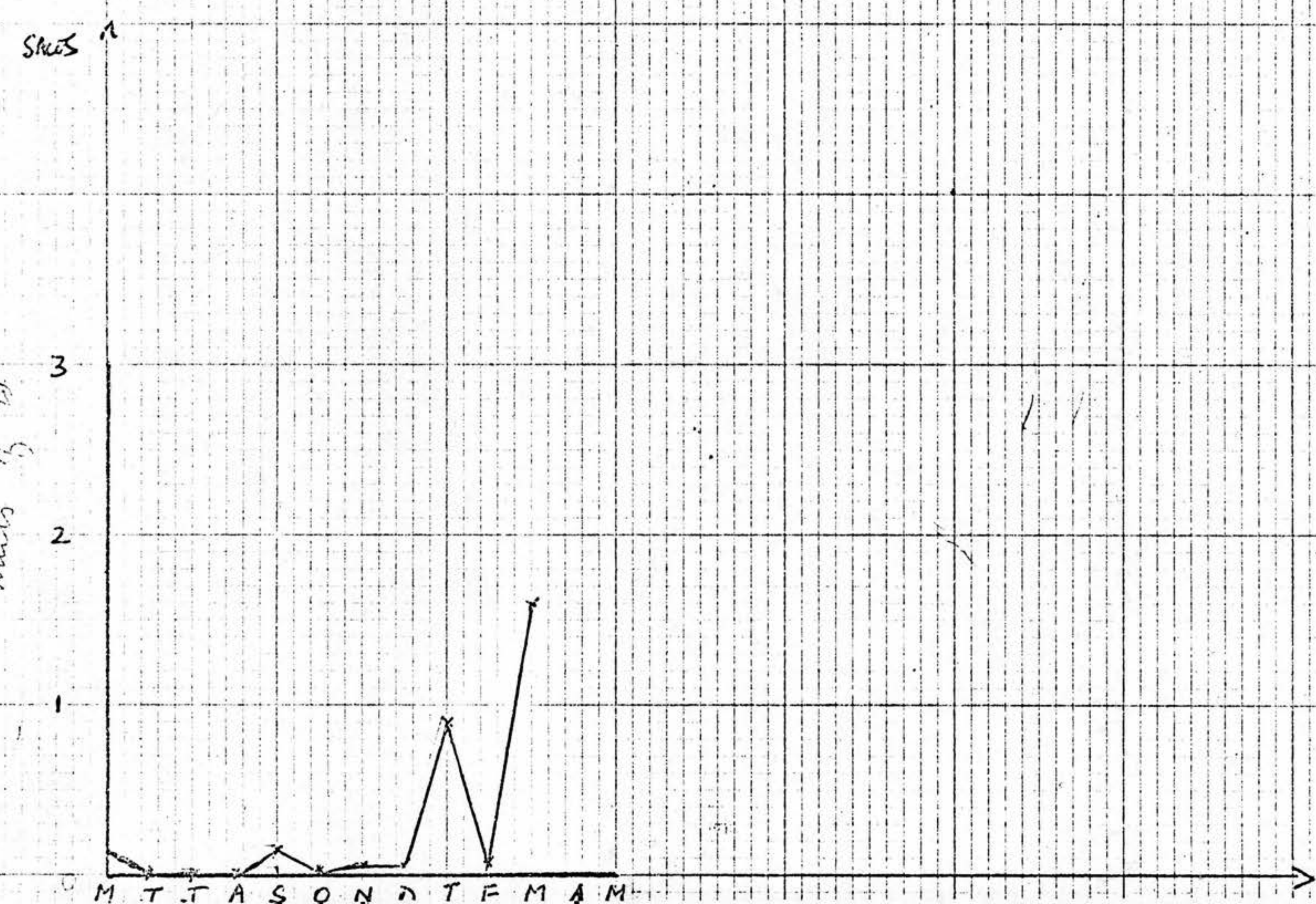
SALES IN QUANTITIES - 7A



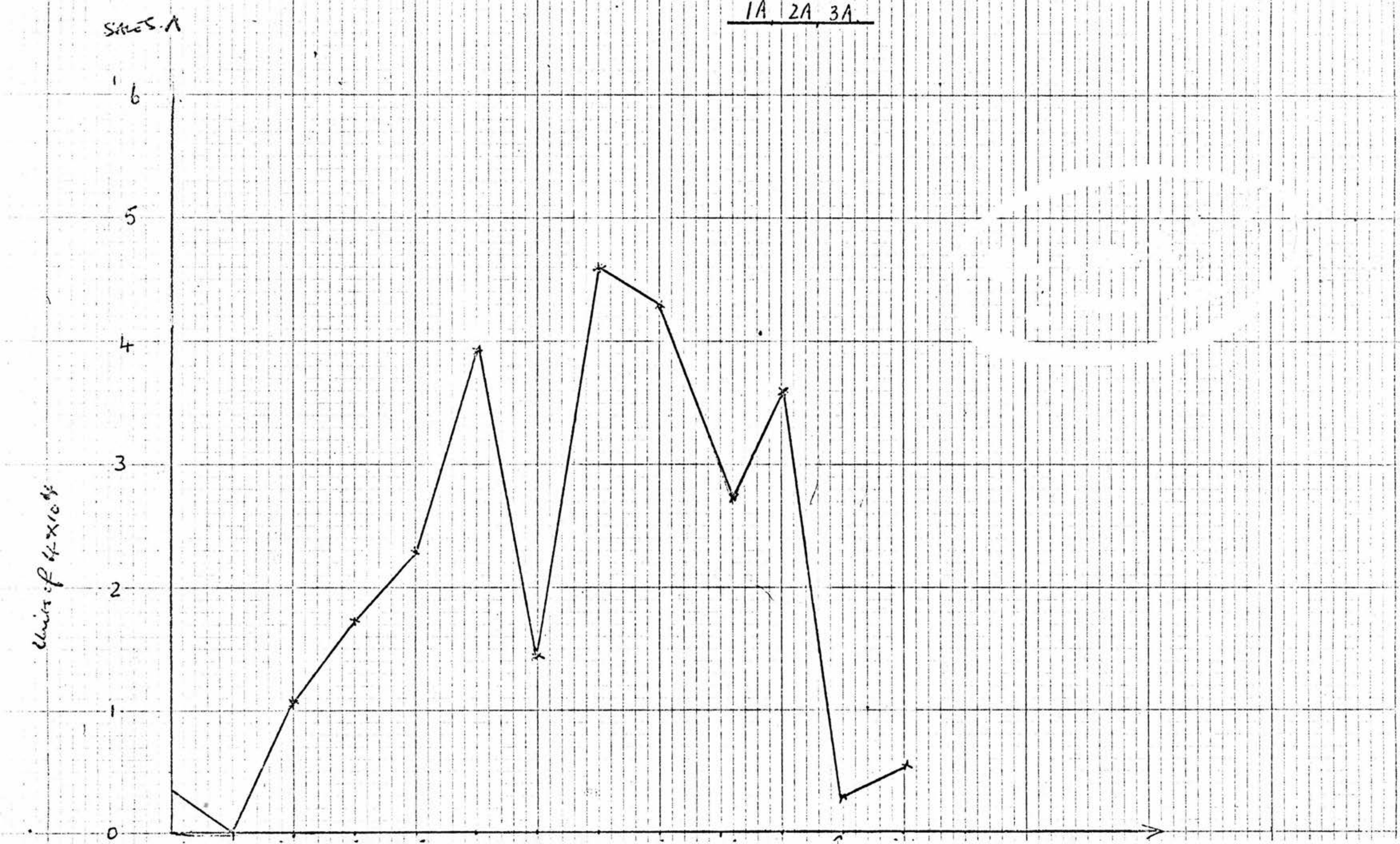
1c SALES IN QUANTITIES. 8A. 316



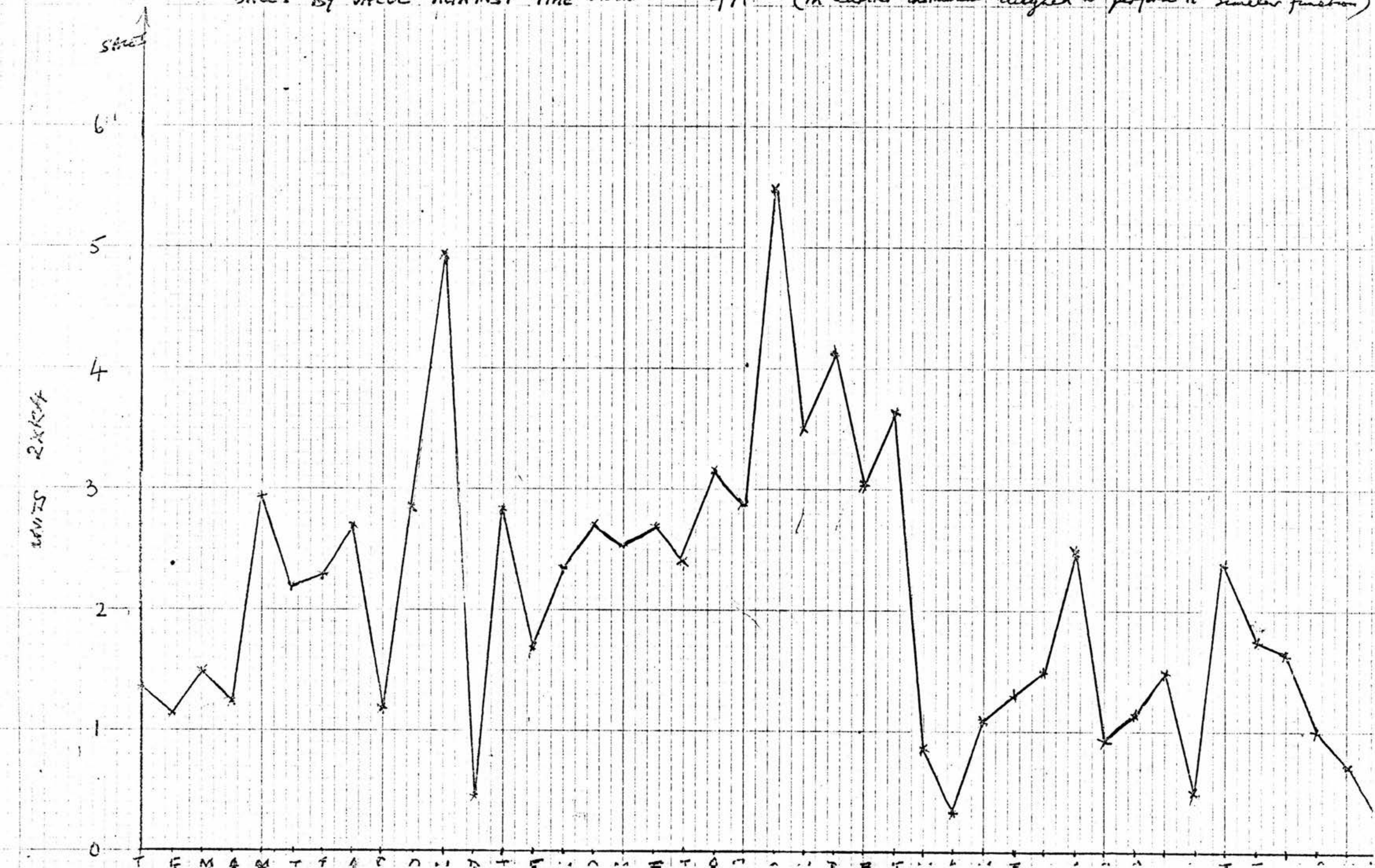
SALES IN QUANTITIES. 9A



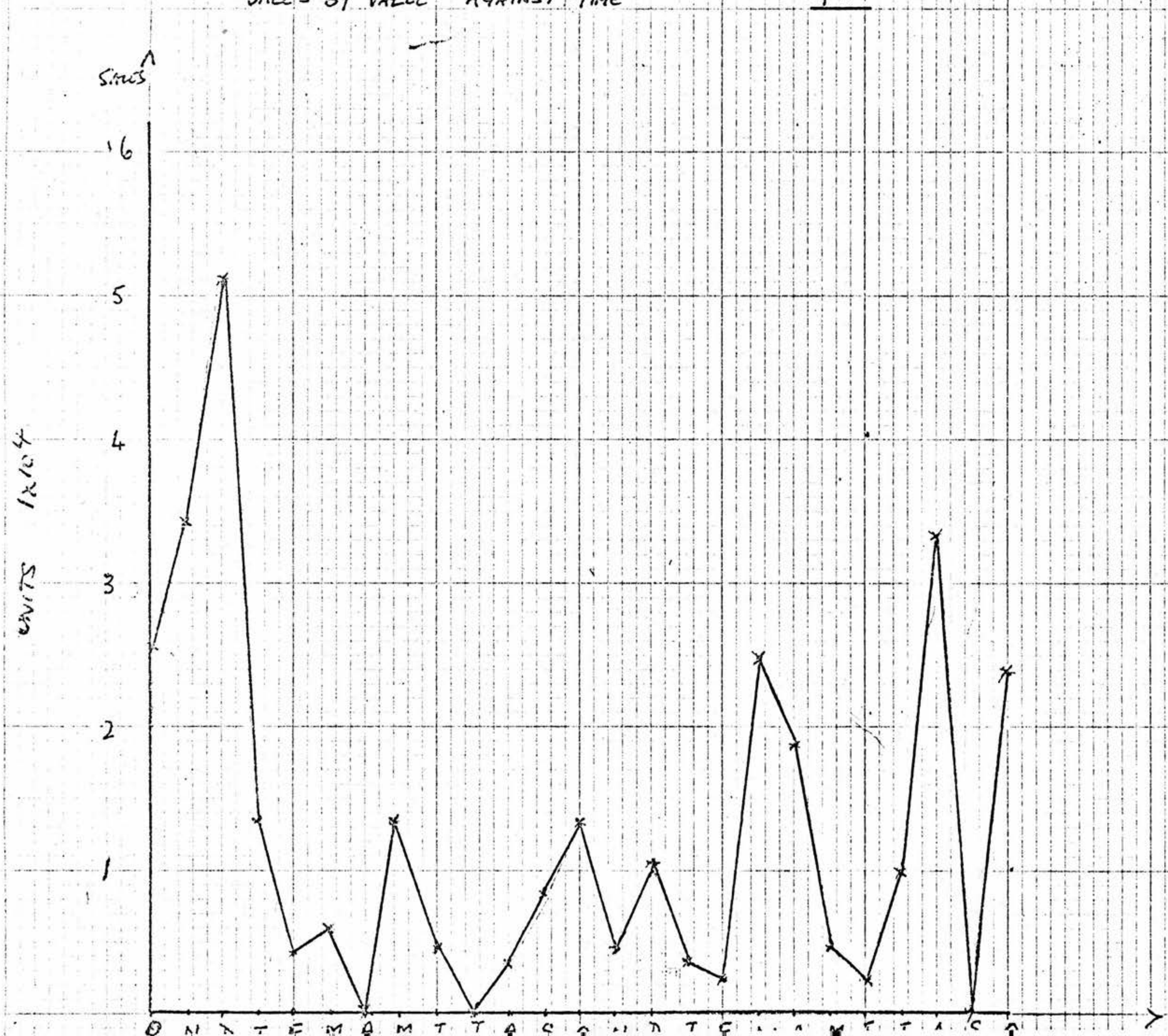
SALES BY VALUE AGAINST TIME



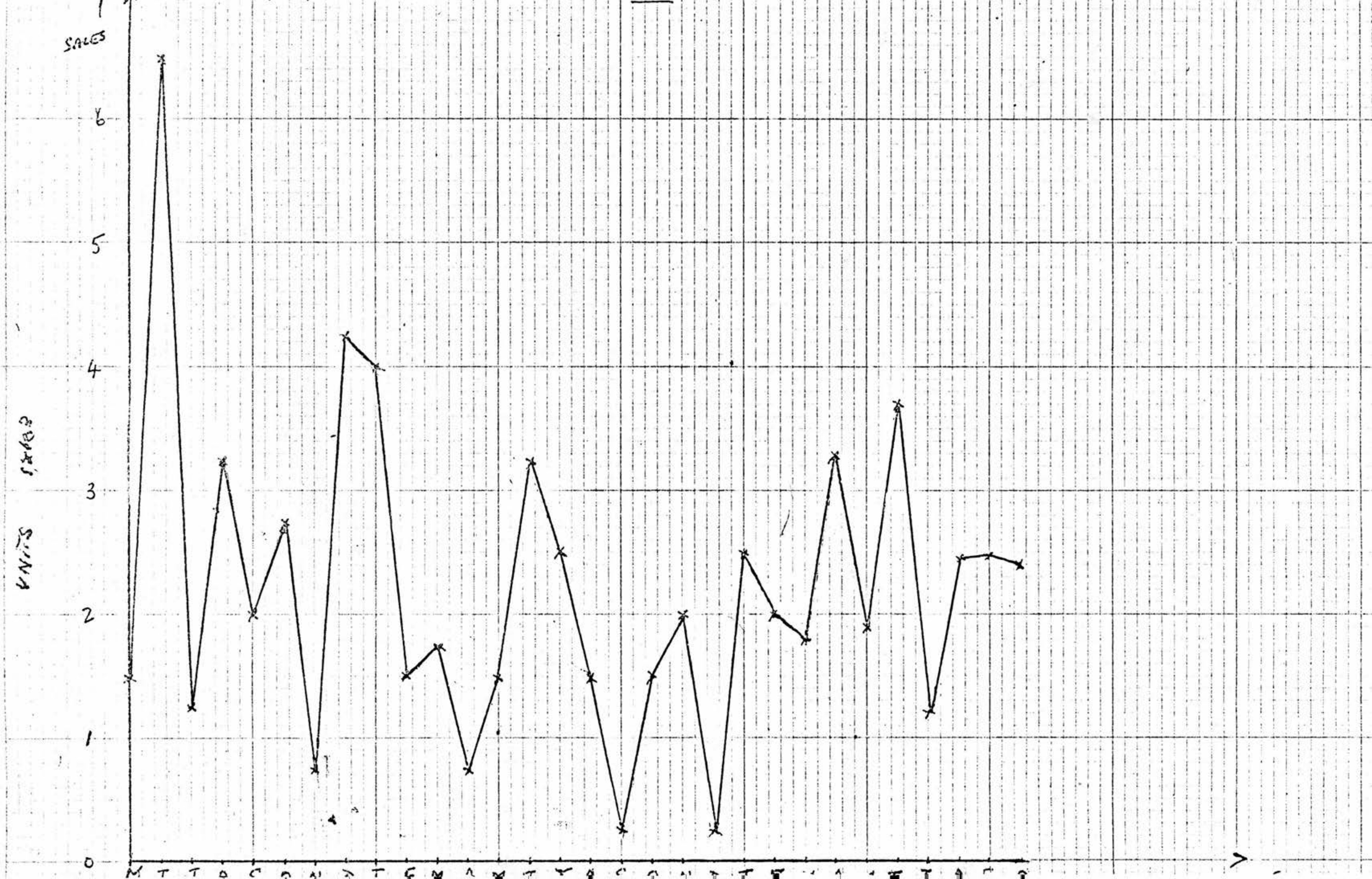
SALES BY VALUE AGAINST TIME 4A (An earlier instrument designed to perform a similar function)



SALES BY VALUE AGAINST TIME - SALES **4A**

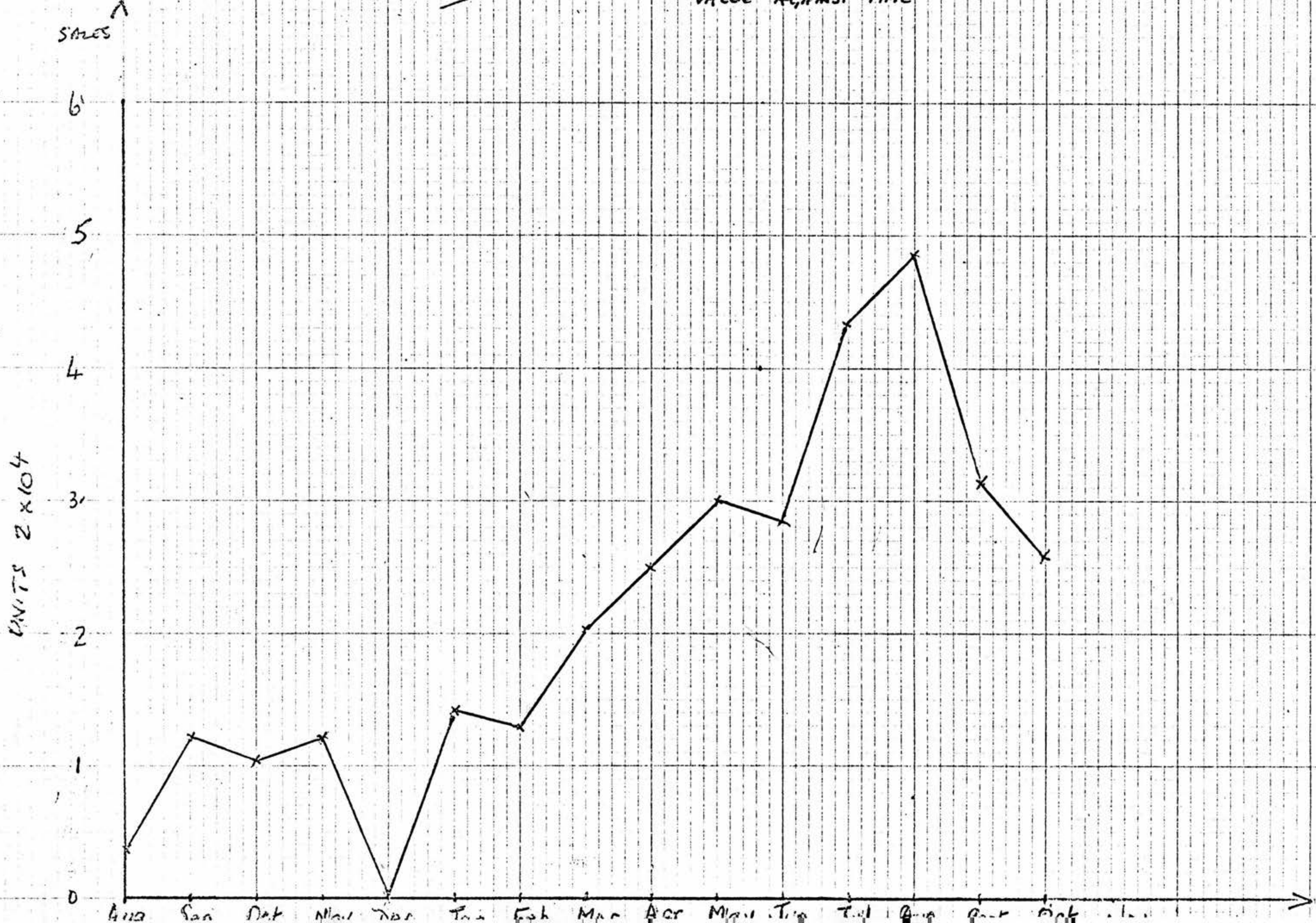


SALES BY VALUE AGAINST TIME SALES 5A

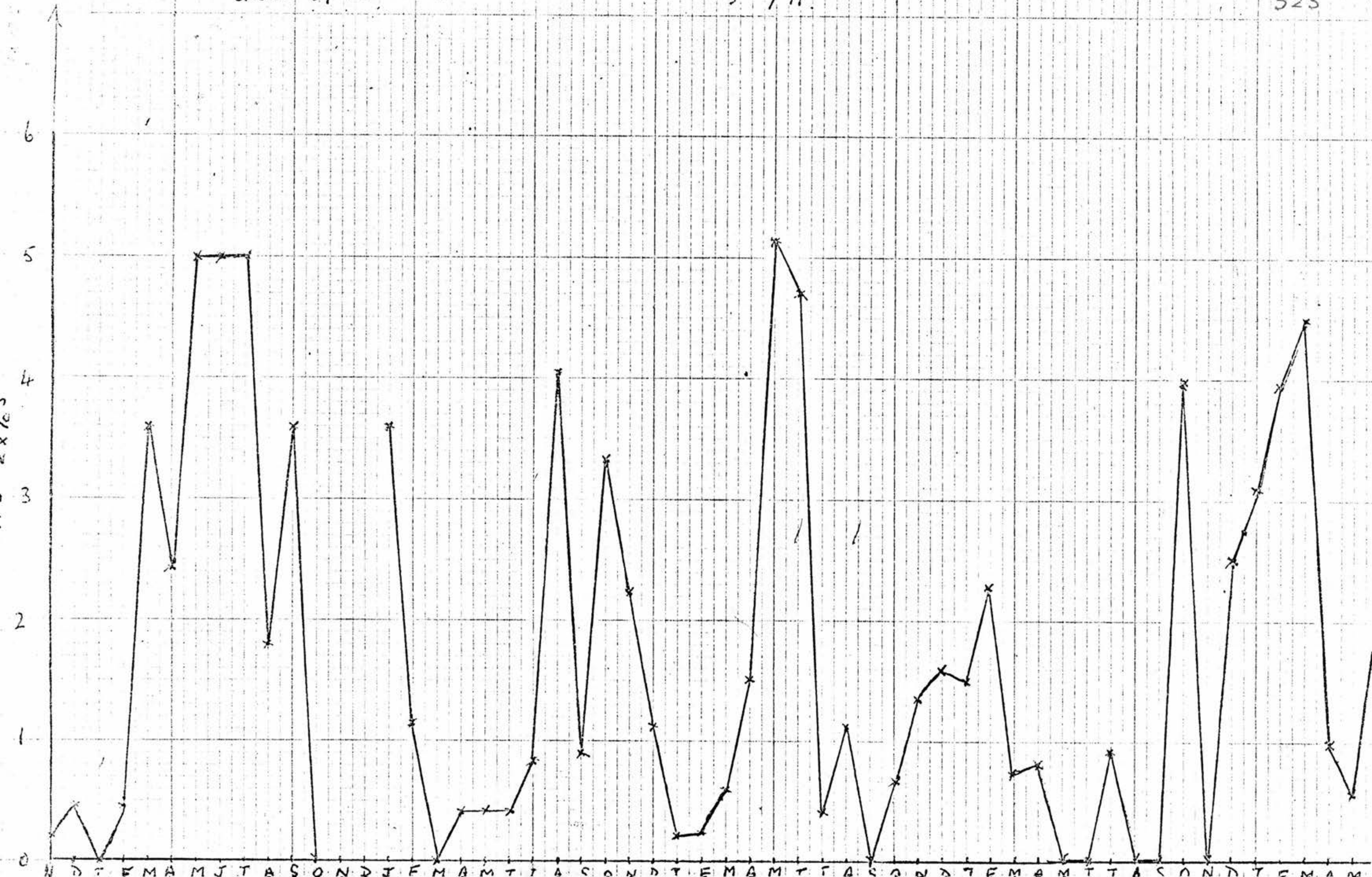


SALES BY VALUE AGAINST TIME

6A

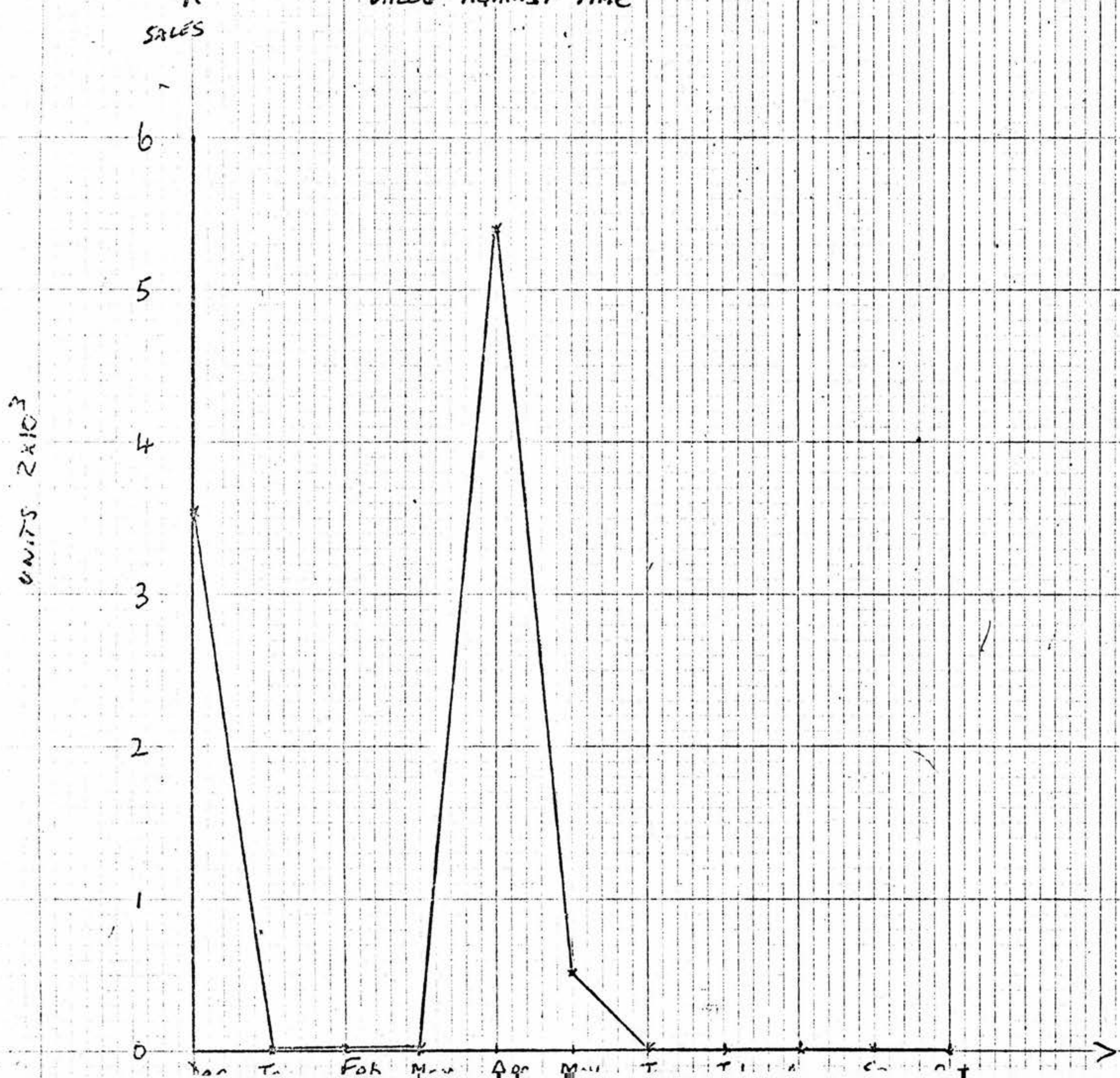


SALES BY VALUE AGAINST TIME SKU 7A. 323



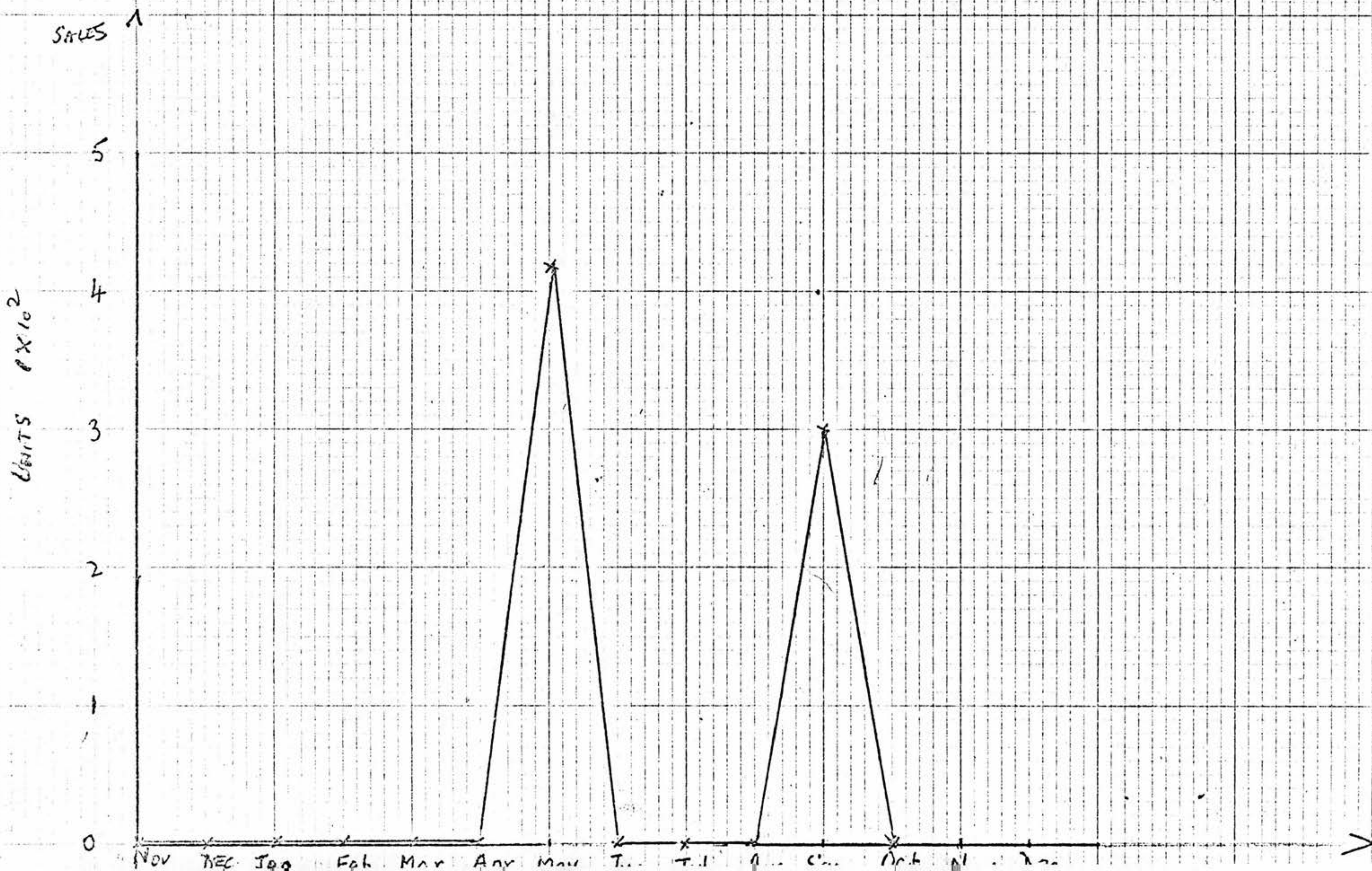
8A

SALES BY VALUE AGAINST TIME



SALES BY VALUE AGAINST TIME 9A

325



of the R & D department in Firm A over the period studied in order to put the cost/benefit analysis into perspective. Over the period of study 31.3% of the resources available for research and development expenditure have been spent on projects that for one reason or another have been shelved. If we allow for the fact that 10-12% or approximately 1/3 of the "wasted" R & D resources have value to the firm through technical learning and "spin-off", then we can say that approximately 80% of the R & D work has contributed to commercially oriented products. This compares with an average percentage for the 10 firms in the electrical engineering industry in the FBI Enquiry[5] of 63.5% (see table 9, P. 86). This would suggest that the efficiency and product orientation of this firm in R & D work is better than average and, if the percentage distribution in the FBI Survey is a criterion, at a high level of efficiency relative to other firms in its industrial sector. Certainly when viewed in relation to manufacturing industry as a whole, on the basis of the 1959/60 FBI evidence, it has operated extremely efficiently in the R & D area.

7.5 Summary and Conclusions

The purpose of this analysis has been to look retrospectively at the results of the research and development work in two firms, A and B. We found initially that records were only adequate enough in A for a detailed analysis to be carried out and that firm B's per-

---

5. Research and Development in Manufacturing Industry, 1959-60. London: Federation of British Industries, 1961

formance could from subjective observation, be considered to be less efficient than A's.

The rationale for the analysis was to learn more about the characteristics of the R & D process by piecing together the past performance and operations of the research and development department.

The main conclusion from the evidence presented here is that forecast inaccuracy is of the same order of magnitude in the two firms studied as in the chemical firms considered by Allen and Meadows. Further, for projects with a high degree of technical advancement the inaccuracy of estimation is of the same order of magnitude as in the military R & D studies of Peck and Scherer and Marshall and Meckling. The behaviour of forecasts through time is found to be unpredictable and indicates clearly that the uncertainty present in the R & D projects is not resolved quickly during the development period. Estimators find it most difficult to forecast costs and likely sales and it is found that relatively small inaccuracies in the forecasts of both these variables can have much larger effects on the measure of worth or likely rate of return from a project.

It is not difficult given the evidence evaluated here to understand why formal models for the selection of R & D work are difficult to construct. Even Firm A which had a formal selection index suffered from large inaccuracies in estimates of costs and sales factors. This suggests that more attention must be given to organisational considerations before formulating project selection models for individual firms. In particular, the relation between estimated and actual project outcomes must be documented retrospectively by each organisation. Inaccuracies in estimation can reflect organisational, social and technical factors present in the individual firm which must be understood in greater depth. In addition, relatively little is known of the nature of uncertainty in R & D projects and more importantly when estimates become sufficiently reliable for a reasonable discrimination between the worth of various R & D projects to be effected.

We must repeat again that inaccuracies in estimates are important because of the uses to which they are put. In the case of research and development these estimates are used as a basis on which firms decide to allocate financial and technical resources between various projects. It is clearly the function of such estimates to improve and stimulate better project decisions. Unfortunately, the evidence shows that estimates are very often unreliable and only become relatively more reliable much later in the development period. Consequently, resource allocation decisions involving the calculation of return factors based on estimates which are so inaccurate that they can only be regarded as worthless are unlikely to be very useful.

We turn in the next chapter to the consideration of ways in which we can harness the knowledge of inaccuracies in past data to improve prospective cost and sales forecasts.

PART III

Chapter 8

METHODS FOR IMPROVING FORECASTS OF VARIABLES RELATED TO R & D PROJECTS

8.0 Introduction

Summers[1] questions whether our knowledge of cost estimating errors can help us to improve future estimates and also ultimately our resulting project selection decision. We concentrate here on the extent to which adjustment of present estimates by means of our knowledge of past estimating behaviour is justified. Summers' position is that the cost estimating position of the recent past is very relevant to assessing the worth of present day estimates.

Of course, the main problem with the analysis of past data on estimating errors is the accuracy of the information on which the analysis is based. Is a difference between an initial estimate and a final value of cost a true measure of inaccuracy? The answer is not necessarily since, for example, it depends on the basis on which the initial estimate was calculated and any subsequent changes in project definition and objectives which affect the magnitude of the final actual value. We know, of course, that Marshall and Meckling's analysis states that provided we treat estimates, however they are generated, as estimates of achieving the project's objectives satis-

1. R. Summers, "Cost Estimates as Predictors of Actual Costs" in T. Marschak (ed.) Strategy for R & D, (Springer-Verlag, Berlin 1968)

factorily by a given date, we can view the difference between initial and final estimates as a measure of the uncertainty actually confronted in making research and development decisions. However, whilst it gives us a measure of the magnitude of uncertainty in broad terms it is not specific enough for operational use in amending present day estimates for known past inaccuracies. To be able to do this we must follow Summers' advice and extract every piece of evidence from the information available. A first step in any analysis of this type must obviously be to enquire into the nature and sources of estimate inaccuracy. Marshall and Meckling suggest that the main source of improvement in estimates of cost, particularly for military research programs, lies in being able to forecast the final design configuration for the project as early as possible. If improvement is not possible in this way then some other method must be found to estimate the extent of bias and potential variability concerning a project's predictions and to adjust existing estimates by means of our estimates of bias and variability. Summers in his study of cost predictions follows the suggestions of Marshall and Meckling and tries to analyse the sources of uncertainty in past data before attempting to construct a debiasing formula. Summers specifically isolates three important variables which influence inaccuracy, namely, the technical complexity of the project, the length of time necessary for accomplishment of the development work and the time at which the estimate was made during the development period. We have discussed earlier the rationale for the influence of these variables on cost estimates and as such we accept their relevance here. Indeed, in the previous chapter similar relationships were found with the much smaller sample of 10 projects analysed as part of this study.

We shall consider in subsequent sections the work of Summers and the adjustment approach adopted in this study. The reasons for each type of analysis will be evaluated and the conclusions and implications for forecast adjustment will be assessed.

8. 1. The Summers Study

We have discussed two features of Summers work already. First, his findings on inaccuracy which agree in broad terms with the existing evidence on military R & D. Second, the variables which explain the major proportion of the uncertainty inherent in cost estimation, namely, the point of time, t, during the development program when the estimate is made; the degree of technical advance, A, of a project; the total length, L, of the development work and the calendar year, T, in which the estimate is made (this tends to allow for the learning process in estimation over time.)

The data available for Summers' analysis consists of 68 estimates of cost for military programs evaluated by the RAND Corporation over a period from 1945-1958.

Summers seeks to explain the value of F, the ratio of actual cost to the adjusted estimate, in terms of the variables t, L, A and T. He decides that the best method of approach is regression analysis and by using regression methods he tries out several functional forms for the relationship between F and t, L, A and T. The most satisfactory functional form is found to be one relating log F, t, L, A and T. Its estimated form is shown in the equation below:

$$\log_e F = \underset{(0.205)}{2.479 + 0.097t} - \underset{(0.019)}{0.032t\ A} - \underset{(0.189)}{0.311A} + 0.015A^2$$

$$+ \underset{(0.002)}{0.008L} - \underset{(0.020)}{0.075\ (T - 1940)} + u$$

This empirical statement of the relation between F and the independent variables is shown by Summers[2] to confirm the empirical hypothesis about the sources of uncertainty inherent in cost forecasts.

To be specific:

(i) for increasing values of t, the expected value of F goes down

(ii) for increasing values of A, the expected value of F goes up

(iii) for increasing values of L, the expected value of F goes up

---

2. See R. Summers (op cit) p. 164

(iv) for increasing values of T, the expected value of F goes down

(v) for increasing values of t, the standard deviation of F goes down

(vi) for increasing values of A, the standard deviation of F goes up

Summers' method is thus a fairly large sample regression analysis of past data. There are four comments that can be made: first, about the usefulness of past data in estimating future forecast inaccuracy. The main problem is that the data is rough and consequently we have to assume that the data was generated in a similar manner with the same commitment of resources in each case and that it is a representative sample from the total population of projects. In addition, we have to assess whether a knowledge of past data is useful in R & D, an area of huge technical uncertainty. If it is useful, how far back into the past is the information valuable for prospective forecasting? It is the view of this author that past data is likely to be of more use in military contract projects, where the procedures and practices in R & D work tend to be much more stereotyped, than in an industrial context.

Second, is Summers correct in his use of regression analysis to amend initial forecasts? Is the technical environment sufficiently damped in its patterns of change for a rigid analytic method of the regression type to adapt to the changing nature of the R & D process?

Third, why did Summers choose a linear model to characterise the nature of the process? He gives disappointingly little justification for adoption of the linear model and the particular functional form in view of his data base of 68 projects. With so many degrees of freedom available, it is surprising that he did not try non-linear models since non-linearities are present in the R & D process e.g. is it really true that learning during development is a linear function of time (see Summers p. 175)?

Fourth, Summers treats only uncertainty in cost estimation in his analysis. From the point of view of the industrial firm and particularly the R & D manager, analysis of sources of uncertainty in market forecasts is useful.

In summary, Summers' study is a valuable one in that the sources of inaccuracy are first assessed and then combined into a formula approach. In the next section the less sophisticated approach of the present study is considered.

8.2 The Adjustment Study

8.2.0 Introduction

The detailed study carried out by Summers consisted of evidence on the cost forecast behaviour of 68 projects. In this short study the sample size is much smaller and refers to the ten projects of firm A whose forecast behaviour has been analysed through time in Chapter

Because the sample size is smaller the analysis necessarily becomes cruder because we have only a small number of degrees of freedom with which to estimate relationships by statistical methods. Further, the fact that the sample is so small means that it will be very difficult for us to establish either the validity of the relationships or to draw any general conclusions.

However, the rationale of the analysis is to consider various approaches for up-dating initial estimates of cost, sales and price in relation to applied research and development projects. Since research and development decision making is a process in which we make an initial decision to undertake a project and then review the performance of that project through time at periodic decision review points, there is a need for initial forecasts to be up-dated and improved through time.

The differentiating feature of the analysis presented here is that it refers to a number of industrial R & D projects and seeks to improve the accuracy of forecasts on price and sales as well as development cost. The analysis takes account of the evidence on the behaviour of forecasts through time by including the forecast value initially, the forecast value at the end of the development period and the actual final value. It considers past data on forecast performance in such a way that it can be used to indicate the general directions in which bias will occur in sales and cost forecasts for R & D projects.

8.2.1. Methodology

For the ten R & D projects of Firm A we have available estimates of development cost, sales and price made at the initial adoption phase of the project and the end of the development period, and also the actual (or estimated actual where sales are still continuing) final values. We use these values to fit a series of simple linear regressions to the data relating final costs, sales, price and return factor values, first, to their estimated values at the end of development and, second, to their estimated initial values and those at the end of the development period jointly. We consider linear functions for two reasons: first, because of their computational simplicity and thus the consequent ease with which they can be performed repetitively in the future by the R & D staff and second, because the small sample of observations available makes sophistication in the functional form of the relationship pointless and the number of possible independent variables that can be included in the analysis limited. We try the analysis as a first step to see if simple rule of thumb formulae can be applied to improve forecasts. We recognise that such simple regression formulae neglect making allowance for known sources of uncertainty in the development process some of which are indigenous to particular organisations. We are asking if simple linear relationships exist between initial values, intermediate values and their final values.

We present the results of the regression analyses (Ordinary Least Squares: OLS) below. It should be noted that there are two separate analyses. Regressions are carried out first for all 10 observations and then for the six observations most representative of the future pattern of firm A's work.

In the price and cost regressions the individual observations are in dollar values. We justify this because most of the projects are of sufficiently similar size and scope that the likelihood of problems of heteroscedasticity and consequent bias in OLS is correspondingly small.

8.2.2. Return Factor Estimates

R_1 denotes the initial return factor estimate

R_2 denotes the estimate made at the end of development

R_3 denotes the actual final value

The regressions are carried out

1) for all 10 projects

2) for projects 1, 2, 3, 6, 8 and 9 considered by the firm to be most useful in terms of representing the future pattern of research work by the firm.

1) 10 Observations

a) $R_2 = 4.51 + 0.01R_1$ $\quad$ $R^2 = 0.63\%$ $\quad$ d. f8

(0.06)

$t = (0.22)$

b) $R_3 = 1.39 + 0.46R_2$ $\quad$ $R^2 = 15.92\%$ $\quad$ d. f8

(0.37)

$t = (1.23)$

c) $R_3 = 1.58 - 0.02R_1 + 0.47R_2$ $\quad$ $R^2 = 17.13\%$ $\quad$ d. f7

$(0.07) \quad (0.40)$

$t = (0.32) \quad t = (1.18)$

2) 6 Observations

a) $R_2 = 5.05 - 0.15R_1$ $\quad$ $R^2 = 5.89\%$ $\quad$ d.f4

(0.30)

$t = 0.50$

b) $R_3 = 2.27 + 0.30R_2$ $\quad$ $R^2 = 5.25\%$ $\quad$ d. f4

(0.63)

$t = (0.47)$

c) $R_3 = 7.76 - 0.7R_1 + 0.025R_2$ $\quad$ $R^2 = 75.47\%$ $\quad$ d. f3

$(0.24) \quad (0.38)$

$t = (2.93) \quad t = 0.07$

8.2.3. Quantity Estimates

Let Q_3 be the final sales per period of time (month)
Let Q_2 be the estimate of final sales made at the end of the development period
Let Q_1 be the estimate of final sales per period of time made initially

Again the regressions are carried out for
a) all 10 projects   b) projects 1, 2, 3, 6, 8 and 9

1) <u>10 observations</u>

a) $Q_2 = 15.45 - \underset{(0.23)}{0.18} Q_1$ $t = 0.78$ $R^2 = \underline{7.15\%}$ d.f. $\underline{8}$

b) $Q_3 = -1.26 + \underset{(0.252)}{0.649} Q_2$ $t = \underline{2.58}$ $R^2 = \underline{45.34\%}$ d.f. $\underline{8}$

c) $Q_3 = -2.95 + \underset{(0.186)}{0.099} Q_1 + \underset{(0.27)}{0.68} Q_2$ $t = (0.53)$ $t = (2.51)$ $R^2 = \underline{47.47\%}$ d.f. $\underline{7}$

2) <u>6 observations</u>

a) $Q_2 = 15.32 - \underset{(0.556)}{0.142} Q_1$ $t = \underline{(0.26)}$ $R^2 = \underline{1.6\%}$ d.f. $\underline{4}$

b) $Q_3 = -0.884 + \underset{(0.226)}{0.667} Q_2$ $t = (2.95)$ $R^2 = \underline{65.58\%}$ d.f. $\underline{4}$

c) $Q_3 = -5.5 + \underset{(0.164)}{0.424} Q_1 + \underset{(0.146)}{0.715} Q_2$ $t = \underline{(2.58)}$ $t = 4.88$ $R^2 = \underline{90.22\%}$ d.f. $\underline{3}$

8.2.4. Price Estimates

let P_3 denote the final actual price
Let P_2 denote the estimated price at the end of the development period
Let P_1 denote the initial estimated price

Again the regressions are carried out for:
a) all 10 projects
b) projects 1, 2, 3, 6, 8 and 9

1) 10 observations

a) $P_2 = \$109.2 + \underset{\substack{(0.35)\\ t=(3.15)}}{1.09}P_1$ $\quad R^2 = 55.31\%$ d.f. 8

b) $P_3 = \$9.69 + \underset{\substack{(0.033)\\ t=(30.12)}}{0.993}P_2$ $\quad R^2 = 99.13\%$ d.f. 8

c) $P_3 = \$49.6 - \underset{\substack{(0.069)\\ t=1.32}}{0.09}P_1 + \underset{\substack{(0.047)\\ t=22.03}}{1.04}P_2$ $\quad R^2 = 99.30\%$ d.f. 7

2) 6 observations

a) $P_2 = \$329.06 + \underset{\substack{(0.533)\\ t=(1.96)}}{1.04}\,P_1$ $\quad R^2 = 49.12\%$ d.f. 4

b) $P_3 = \$-52.85 + \underset{\substack{(0.027)\\ t=(37.99)}}{1.014}\,P_2$ $\quad R^2 = 99.72\%$ d.f. 4

c) $P_3 = \$-13.85 - \underset{\substack{(0.047)\\ t=(1.68)}}{0.079}\,P_1 + \underset{\substack{(0.031)\\ t=(33.45)}}{1.051}\,P_2$ $\quad R^2 = 99.85\%$ d.f. 3

8.2.5. Cost Estimates

The analysis of this data was carried out in a different way in order to compare the cost results obtained from Firm A with the chemical laboratory evidence given by Meadows in his study. The projects were first divided into commercial successes and failures and separate regression analyses were carried out for each category. We find that there are five commercially successful and five unsuccessful projects. It was decided after thorough discussion with project personnel to eliminate project 8 from consideration and this reduced the unsuccessful category to 4 projects. There were convincing arguments to suggest that project 8 was atypical in cost estimation because of management interference with the project - this drawback did not affect price and sales estimates.

Let C_1 be the final development cost
Let C_2 be the initial estimated development cost

1) Commercially Successful Projects

$$C_2 = -10791\$ + \underset{\substack{(0.63)\\ t=(5.37)}}{3.36}\, C_1 \qquad R^2 = 90.57\% \quad \text{d.f. } 3$$

2) Commercially Unsuccessful Projects

$$C_2 = -16886\$ + \underset{\substack{(0.803)\\ t=(3.51)}}{2.822}\, C_1 \qquad R^2 = 86.04\% \quad \text{d.f. } 3$$

These results were then compared with the same type of regressions calculated here from the data provided by Meadows* for chemical laboratories A and B. The regressions are presented below:

Meadows Chemical Laboratory A

1) Commercially Successful Projects

$$C_3 = 5232\$ + 0.138\, C_1 \qquad R^2 = 5.2\% \text{ d.f. } 10$$
$$(0.186)$$
$$t = (0.74)$$

2) Commercially Unsuccessful Projects

$$C_3 = 6489\$ + 0.698\, C_1 \qquad R^2 = 7.61\% \text{ d.f. } 9$$
$$(0.810)$$
$$t = 0.86$$

3) Technically Unsuccessful Projects

$$C_3 = 347.1\$ + 2.51\, C_1 \qquad R^2 = 47.93\% \text{ d.f. } 5$$
$$(1.17)$$
$$t = \underline{(2.15)}$$

* Note: D. Meadows has given permission for me to use data from a working paper

Meadows Chemical Laboratory B

1) Commercially Successful Projects

$$C_3 = \$528.4 + \underset{\substack{(0.125)\\ t=\ (4.75)}}{0.595}\ C_1 \qquad R^2 = \underline{73.80\%} \text{ d.f. } 8$$

2) Commercially Unsuccessful Projects

$$C_3 = -4255.1\$ + \underset{\substack{(1.64)\\ t=\ (6.66)}}{10.89}\ C_1 \qquad R^2 = \underline{84.70\%} \text{ d.f. } 8$$

8.2.6. Comments on regression results

Some comments can immediately be made about the results of the analysis. First, it is not surprising given the nature of the return factor formula and the inaccuracies that exist in the benefit and cost forecasts that simple relationships between estimates of return factors made at different points in time during the project do not exist. In fact the only relationship of any significance is 2) c) where approximately 75% of the variance in the final return factor is explained by the combination of the R_1 and R_2 values but only the regression coefficient of R_1 is significant at the 5% level under a "t" test. This might suggest that with larger samples a relationship between R_3 and R_1 might be present but it is unlikely to be of operational use because of the biases inherent in the return factor measure itself.

Second, the results on quantity estimates confirm that no linear relationship of any significance exists between estimates made initially and those made at the end of the development period. However, there is some evidence from equations lb, lc, and 2b, 2c that the final sales value is related to a combination of Q1 and Q_2 particularly in the case of the six observations. Yet in no case, given our previous knowledge that quantity forecasts oscillate about the true value through time, can we say that a rule of thumb linear adjustment formula will necessarily improve future sales forecasts.

Third, in the case of price forecasts we find very strong linear relationships between final prices and those estimated at the end of development. This is a reasonable finding since a major uncertainty in the pricing analysis for a project in this firm is the development cost. Linear relationships between initial prices and P_2 are not as strong but are just about significant in both cases. Again the analysis confirms that the major sources of uncertainty in pricing for this firm are resolved by the end of the development period.

Fourth, in Firm A there appears to be a strong linear relationship between final costs and initial costs for both technically and commercially successful projects. This appears also to be the case for Chemical Lab B but mysteriously not for Chemical Lab. A. Therefore, the analyses of industrial R & D so far available do not agree with each other even on the strength of the relationship between initial and final values. Further, if we compare our Firm A with Meadows' Firms A and B, we find that the regression coefficients for Meadows A and B are much larger for technically and commercially unsuccessful projects than for commercially successful projects whereas the reverse is true for our firm A. This makes it clear that although linear adjustment formulae for up-dating cost estimates may be valuable for firms, the form and extent of the significance of the relationships will vary between firms.

The analysis though very crude suggests that cost and price forecasts can be adjusted by some sort of debiasing formula. If more observations on projects had been available we could have dealt with a larger number of independent variables and different (and maybe non-linear) functional forms for the regression equation. However, we can assert that the crude methods of this section are of no use in adjusting forecasts of return factors and sales which tend to ascillate around their final values through the life cycle of the project.

8. 3. Conclusions

Most of the regressions show clearly that the practice of up-dating initial estimates by working with past data is generally inadvisable. The regressions also confirm that large errors are present in forecasts made for R & D projects.

Chapter 9

AN APPRAISAL OF THE USE OF THE CASE STUDY APPROACHES IN BUILDING THEORIES AND MODELS FOR THE DEVELOPMENT PROCESS

The aim of the studies in parts two and three of this thesis is to acquire knowledge about the nature and economic characteristics of the development process, and, in particular, to provide evidence on the development process which is not presently available in the literature. It is fair to say that the studies have thrown light upon the nature of uncertainty in the R & D process and have presented new evidence on the learning process in development for a number of R & D projects in an electronics firm. However, it is reasonable to gather our sails for a moment and summarise the theoretical framework on which we can build in Part IV. In short, what have we learnt from Parts II and III and how will this affect our use of the economic evidence summarised in Part I?

In earlier chapters and here we stress the virtues of the integrated approach to model building, that is, carrying out a detailed preliminary analysis of economic and environmental factors in the firm before commencing on the model building phase. This approach implied that we first form a descriptive theory of the

R & D process at the firm level. However, we are more interested in using this observation of firm behaviour to enrich a normative theory of decision making in R & D at the firm level.

In Part II we first identify the stages in R & D process. These consist of the initial search for and generation of possible projects, the production from the potential projects of a flow of new projects in the firm and the transmission of these projects into commercially viable end products. Decisions have to be made throughout this process. The size of the budget for R & D work, the acceptance or rejection of a potential project and the review of existing projects for continuation are some of the areas in which decisions are made by managers of the R & D function within the firm. Any theory of decision making must consider the areas in which decisions are made. Equally important is the environment and conditions under which decisions are made and this requires a detailed analysis of the nature of development activity.

There is some truth in Klein's[1] view of the groping uncertain nature of R & D activity in view of the evidence presented in the uncertainty resolution section in the third part about the fact that estimates of costs and other variables only get fairly accurate after a significant proportion of the development time has elapsed. There is clear evidence that there is some sort of learning process

---

1. B. V. Klein, "The Decision Making Problem in Development", in R. R. Nelson (ed) <u>The Rate and Direction of Invention Activity</u> Princeton, 1962

during development in that estimates of cost improve through time and become accurate once the final design and detailed specification are approved. But the slow process of uncertainty resolution throws into open debate the policy of operating a parallel path R & D strategy[2] in industrial R & D. The rationale for a parallel path strategy is clear in military R & D where the work is at the frontiers of technical knowledge and thus very little is known initially about design and specification of a military R & D project. Industrial R & D is as we have seen more applied and concrete in nature and whilst a parallel path strategy might be useful, it would probably be costly. This means that, whilst the parallel approach will always improve knowledge and thus estimates of a project's potential performance, the monetary gain to the firm from the improved knowledge may be far less than the cumulative costs of pursuing a number of approaches for each of the potential projects being considered until a selection of the best approaches and projects can be made.

The papers by Enos, Peck, Marshak and Nelson[3] on case studies of various inventions suggest that it is a reasonable simplication to ignore the complications pointed out by Klein and to treat the allocation of resources to R & D projects as being capable of explanation in terms of a simple maximisation model. The evidence from the present studies confirms that it is reasonable to view the motivation for undertaking R & D work as being the

2. The Parallel Path Strategy was first presented by R. R. Nelson: "The Economics of Parallel R & D efforts" RAND Corporation, 1959.

3. See R. R. Nelson (ed) Rate and Direction of Inventive Activity, Princeton, 1962

maximisation of some profitability or value function. Our study of the processes of decision is important in this context in so far as it tells us that it is reasonable to make the assumption that managers in R & D act as if they seek to maximise profitability.

One of the major decision problems in industrial R & D is the allocation of resources to particular projects i. e. the project selection problem. Any model to explain allocation decisions must be based on a minimum amount of information. In the decision process work we saw that the information systems in firms A and B differed in their level of formality and information content, B presenting relatively little information for either decision making or control purposes. Yet we consider that it is perfectly reasonable to expect firms to generate a certain amount of data for decision making purposes which can be used as the information framework for an allocation model. At the same time we recognise in our analysis that there are undoubtedly cost elements involved in the provision of management information and control systems for decision making.

In our study of decision making in firms A and B we saw that A had a procedure for routinising information gathering for R & D projects and calculating measures of project worth. In B the procedures were informal and personal to the R & D decision maker. We take the position here that if information is being generated about R & D projects, then there should be a process or procedure to minimise the need for the decision maker to process and summarise information. Such an idealised process is summarised in the block diagrams in the summary to Part II. We have seen that necessary inputs to such a process are a priori estimates of project worth for preliminary screening of potential projects. It must be noted that these estimates of project worth must make allowance for all the relevant dimensions of project costs including search costs for potential projects and must be plausible measures for decision making purposes (for example, allowance should be made for the discounting of future benefits to their present value equivalents). Further, much more explicit treatment has to be given to the uncertainty inherent in the R & D process in developing measures of project worth. The findings in Part III of the thesis show clearly the huge inaccuracies that exist in forecasts of economic variables related to R & D projects. There is, thus, a need to incorporate concepts from probability theory to develop subjective probability forecasts for those economic variables.

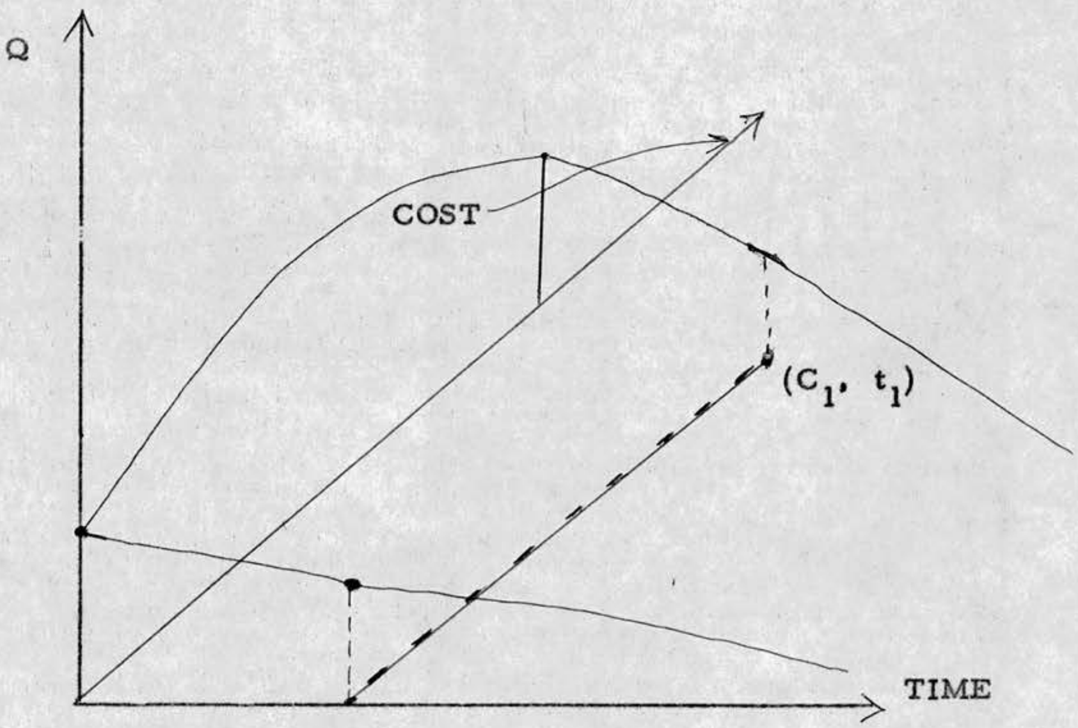
It is equally clear that any formal model will be useless unless problems of obtaining estimates for variables related to R & D projects are solved. The apparatus of the modern concept of personal probability provides a basis for incorporating uncertainty into initial estimates and Bayesian concepts of conditional probability give us the means by which we can up-date estimates through time to take account of the extent of learning over the stages of the development period.

If better measures of project worth can be developed and tested and if we also accept the simplistic objective of profit maximisation for R & D work, then the allocation problem can be formulated as a maximisation problem subject to constraints determined by the nature of the operations of the individual firm. This formulation can be solved in terms of the range of currently available constrained optimisation techniques.

The final problem in R & D work is the need for continual re-evaluation of existing projects at review points in order to compare them with newly generated projects. Typically, the decision maker might have to recommend the curtailment of an ongoing project in favour of a new project in a situation of scarce budgetresources under a profit maximisation objective. It is clear in this situation that we have a series of sequential allocation decisions which can be modelled under certain assumptions by techniques such as dynamic programming.

We have so far seen that the R & D process is a multi-stage process in which uncertainty is present up until a late stage in the development phase. It is evident that the "invention-innovation" framework is an useful basic model for the R & D process and it is reasonable to consider the aim of the invention stage for a given project to be the achievement of a given quality, Q, or level of technical success subject to cost, C, and time, t, constraints. Thus, $Q = f(C, t)$[4, 5].

The function $Q = f(C, t)$ relates quality or level of technical success at the end of development to cost and time where there can be trade-offs between cost and time to achieve an end result of given quality. Clearly the objective of the development process is to achieve as high a quality level as is possible commensurate with the given cost/time configuration. This situation can be depicted graphically as follows:



---

4. T. A. Marschak, "Models, Rules of Thumb and Development Decisions", in B.V. Dean (ed), O.R. in R & D, (Wiley, 1963)

5. T. A. Marschak, Chapter 5, in Strategy for R & D, ed. T. Marschak et al (Springer-Verlag, 1968)

$Q = f(C, t)$ is depicted in three space and our clear objective in the process is to find the maximum point in Q space for a given project. Choice between projects is determinedby forming a ranking in descending order of Q and picking those projects with the highest Q values subject to constraints on time and money. For any quality function Q (however we measure Q) we can determine the maximum point quite simply if we assume that cost is a function of time. This assumption can be justified quite reasonably if we review the evidence on the resolution of uncertainty in cost forecasts over time where we see that C changes with time in a slightly non-linear way and concerges on the final value after about half the development period.

Consider $Q = f(C, t) \qquad C = f(t)$ i.e. $Q = f(t)$

$$\frac{dQ}{dt} = \frac{\partial f}{\partial C}\frac{dC}{dt} + \frac{\partial f}{\partial t}$$

This assumption that $C = f(t)$ in effect makes Q a function of a single variable time. Then $\frac{dQ}{dt} = 0$ gives the maximum quality point i.e. where $\frac{\partial f}{\partial c}\frac{dC}{dt} + \frac{\partial f}{\partial t} = 0.$

Whilst the above $Q = f(C, t)$ analysis is useful conceptually it raises severe problems about the measurement of quality. In most econometric work price is taken to be the indicator of quality but in this situation how is price defined. In firm A $P = f(C)$ i.e. the priee of the end product is related to development cost which would suggest that maximisation of quality or level of technical success with respect to time is nearly equivalent to the maximisation of development cost with respect to time. Certainly, it is true that performance or technical objectives on military projects are achieved in reasonable time with the inevitable trade-off, cost escalation. Whilst this could be explained in terms of cost maximisation it is more likely to be a function of military contract estimating procedure with its emphasis on cost plus contracts. In the cost plus situation the contractor will maximise his profits by maximising his cost.

Clearly, the maximisation of $Q(C, t)$ with respect to constraints on cost and time could be formulated as a problem in constrained optimisation by calculus. The model has some value in viewing the development stage and can provide a basis for a Bayesian treatment of the R & D process.

Arrow[6] puts forward the view that Bayesian methods can provide a framework within which the knowledge producing activities of research can be analysed. He views the research and development process as being ultimately concerned with the

---

6. K. J. Arrow, "Classificatory notes on the Production and Transmission of Technical Knowledge", AER Papers and Proceedings, May 1969.

problems of uncertainty reduction which have been the topics of interest in research in statistical decision theory. The R & D decision maker has a number of possible activities or projects and he is required to make a choice between pursuing some or all of these activities when the physical outcome of the activity and the information required are relevant dimensions of his decision function. In industrial R & D Mansfield has shown that the bulk of R & D expenditures are actual steps in the production process - design, engineering and other costs - and Arrow used this statement to develop his Bayesian view of the process. Each stage in the process involves uncertainties about cost estimates and eventually about final demand patterns for the output. But as each stage transpires something is learnt about the process to enable the decision maker's subjective prior probability distribution over the outcomes of a particular R & D activity to be revised into posterior probabilities by means of Bayes theorem. Arrow, however, is not specifically interested in developing the Bayesian microeconomic view of the development process but in aggragating from an individual theory to a collective theory of the production of technical knowledge.

The aim in this study is clearly microeconomic and we propose that statistical decision theory is an operationally useful theoretical framework for the R & D process. We have seen from Part III that it is very difficult to justify the use of retrospective evidence on the parameters of the R & D process e.g. average cost estimation errors to improve our estimation of the future performance of the process. Evidence on past uncertainties cannot be used to mechanically revise future estimate on new projects but it can be helpful in improving the R & D manager's initial prior probability distribution over the outcome space by making him more aware of the source and extent of past inaccuracies. The main reason for our lack of confidence in past R & D work is the technically uncertain and dynamically changing nature of R & D activity. In essence, the only useful evidence by which predictions about the final outcome space can be amended is evidence from the development project itself through time. This corresponds with a view of the R & D process as a stochastic uncertain process which generates its own information flows. In such an environment the concept of personal or subjective probability is valuable because the probabilities over the uncertain states of nature e.g. cost, characterise the decision maker's beliefs about the project before research work begins. At that stage the personal probability distribution over the states of nature, e.g. cost, time, etc. and the associated prediction in the outcome space is the sole information base on which the decision maker can evaluate whether or not to proceed with a given project. Any projects which pass this initial project selection stage are passed on to the development phase where the decision maker may or may not decide to review their progress at a number of review points during the development period. If he does not then the projects will continue over the development period purely on the basis of the decision maker's prior evaluation of the odds. However, if there are a number of review points over time, at each review point the decision maker will have a number of alternative strategies open to him. He will have information available from the progress of the R & D work up until the review point and he will have the option of either curtailing R & D work because he has sufficient knowledge of the prevailing state of nature or continuing R & D at a given cost to find out more information about the states of nature. With either option he has the opportunity of buying information at a given cost to improve his knowledge of the research process. However, whatever decisions he makes he must act in accordance with the posterior probabilities on the states of nature obtained by the use of the Bayes formula for conditional probabilities.

Thus Bayesian methods have an intuitive appeal in characterising the multi-stage decision nature of the R & D process and further provide a means for formalising degrees of belief about projects both a priori and a posteriori. It is considered that the microeconomics of the R & D process in an industrial context are better explained by the Bayesian model than the parallel path strategy developed by RAND, which despite its elegance is more applicable to very technically advanced projects of the kind sponsored under military contracts. There is not really such a problem of choosing between various possible approaches to tackle a given project in industrial R & D. On most projects the preliminary evaluation determines the specification, design configuration and method of approach and it is only when an industrial R & D project becomes complex that design configurations change appreciably over time. Of course, in this situation the combination of the parallel path approach and the Bayesian approach is extremely useful as can be seen from Marschak's valuable contributions to the literature.

If we return for a moment to the $Q = f(C, t)$ formulation of the development or "invention" phase of the R & D process, this relates the achievement of the best possible quality to cost and time dimensions (quite clearly others could be added). But we must also consider the innovation phase of the process, the transformation of a technical success at a given cost into a commercially viable end product. This is difficult if a poor end quality level is achieved. If, however, a firm achieves high quality it generally has no problem in selling the product. In the first situation of poor quality it is always true that you can sell anything provided you try hard enough but the achievement of extra sales has to be "traded off" against any increase in marketing and sales costs. It is useful to remember two parts of the evidence from Part III in this context.

First, in Firm A we found that technically successful projects tend also to be commercially successful in terms of the firm's objectives if we disregard projects, e.g. contracts, which are not typical of the firm's R & D activity. Second, the major part of uncertainty in price and cost is resolved by the end of the development period at which stage the sales mix required to produce orders can be amended to ensure commercial success. Of course, the major problem is still to estimate sales at this stage accurately but with the technical knowledge of the end product that is available, the decision maker can amend his beliefs of sales patterns and revise his predictions of the final outcome. The process of commercial exploitation of a project is thus dependent on the ability and skill of the firm's marketing employees and any decision maker's prior probabilities on demand patterns will reflect his awareness of the firm's ability or inability to commercialise a project.

In summary, the Bayesian approach with its formal treatment of the uncertainties inherent in , and the multi stage nature, of the R & D process is the most fruitful framework for a micro-theory of development. In the next section we try to build on the structure suggested in this chapter to build an useful normative approach to decision making in industrial R & D.

It is true that the studies in Parts II and III refer to only two firms in the electronics sector of industrial R & D. However, by comparing questionnaire answers for A and B with the Clark study mentioned earlier we find that A and B are reasonably representative of the typical electronics firm. Thus, our normative approach will have relevance for electronics firms but should apply with modifications to any R & D environment.

We turn now to Part IV in which we develop the Bayesian method of viewing the R & D process.